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The Reflection and Emission of Electromagnetic Radiation by Planetary Surfaces and Clouds

by

D. G. Rea

and

W. J. Welch

(NASA CR 52222)

Space Sciences Laboratory
and
Department of Electrical Engineering
University of California U.
Berkeley ~~4, California~~ 1608009

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by Planetary Surfaces and Clouds

To review adequately the immense amount of data encompassed by the title would require several large books. All of the numerous planetary observations from Earth have relied on some form of electromagnetic radiation, generally reflected solar radiation in the visible part of the spectrum. For the most part these have not involved any spectral resolution other than that provided by the eye. While such observations have been valuable in providing qualitative information on the planets they are generally too coarse to answer important questions such as the composition and roughness of a surface, and the parameters of clouds. Admittedly this thesis is not universally accepted since, for example, some authors, after having observed a wide range of colors for the dark areas on Mars, have inferred the presence of vegetation. The evaluation of these conclusions, which must of necessity be subjective, with the factors of chromatic aberration of refracting telescopes and contrast also entering, is bound to be very uncertain and subjective in itself. Accordingly we will not attempt this task and suggest that any reader so interested consult some of the major reference works cited. The present paper then will be concerned with quantitative observations possessing a certain amount of spectral resolution.

Even when the topic is restricted to quantitative work the area is still considerable. To make it manageable we will lean heavily on recent monographs and review papers for detailed treatment of the earlier literature. The pertinent observations and conclusions will be extracted and used as a starting point for a discussion of the more recent work. Our treatment will be somewhat more complete for the surfaces than for the clouds. Interpretations of observations of cloudy atmospheres are very complex since they involve the interplay of particles or droplets with the gaseous constituents. The number of independent parameters is large so that in general an unambiguous interpretation is difficult.

It is hoped that in the process of describing the current situation no significant papers are overlooked--our apologies are tendered in advance to the authors if this occurs.

I. Theory

Plane Surfaces

The simplest starting point is the consideration of a plane boundary between air and a semi-infinite, homogeneous, absorbing dielectric. We will take the refractive index of air as 1.0 and write the complex refractive index of the medium as

$$n' = n - ik \tag{1}$$

where n is the real part and k is the extinction coefficient. (The absorption coefficient, α, in $I = I_0 \exp(-\alpha x)$, is related by $\alpha = 4\pi k/\lambda$). Then the reflection from the interface is specular and the magnitude of the reflection coefficient for an angle of incidence θ can be calculated using Fresnel's equations (Simon, 1951). In general the reflection coefficients are different for the polarization components parallel and perpendicular to the plane of incidence, but at normal incidence they are equal and are given by

$$R_{\perp} = R_{\parallel} = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} \tag{2}$$

The formulae for specular reflection from the plane surface of an absorbing medium have been used extensively by Simon and others to determine the optical properties of materials. Different experimental procedures have been followed. In one the reflection coefficient is measured near normal incidence and a model assumed for the absorbing mechanism to relate n and k . In another the reflection is measured over a wide range of wavelengths at normal incidence and the Kramers-Kronig relation used to derive n and k. A third technique has been to measure the reflection at two widely different angles of incidence, and then calculate n and k. By these means much information has been obtained in the laboratory on materials such as quartz, glass, the alkali halides, benzene, etc. However they have not found application as yet in planetary observations due to surface irregularities.

As an indication of what one can expect when working with an absorbing medium, we have calculated the reflection coefficients for a material possessing an isolated medium intensity absorption band. The values of n and k, were calculated from formulae in Slater and Frank (1947) and were then used to calculate the reflection coefficient near normal incidence, figure 1. For such a band the reflection is determined essentially by the value of n so that the S-type dispersion contour is observed in the reflection coefficient as well as in the real part of the refractive index. For larger angles of incidence the reflected radiation becomes polarized and the spectral contours are altered. An example of an S-type reflection curve is presented by lucite, figure 2. The C = O stretching band of this substance is a good example of an isolated medium intensity infrared band.

When the band intensity increases the reflection coefficient increases, the peak broadens and shifts to higher wavenumbers. High reflectivities of the order of 0.9 can thus be obtained for the very intense bands of inorganic crystals. This type of reflection band has long been used in far infrared spectroscopy to isolate a narrow wavelength region and is known as a Reststrahl. A typical example of such a feature is demonstrated by Li F, figure 3, which has been studied recently by Gottlieb (1960).

The thermal emission of a semi-infinite, homogeneous, isothermal dielectric having a plane interface with the atmosphere is of course not that of a black-body at the same temperature but is only a fraction of it. This fraction is called the emissivity ϵ and is related to the reflectivity by Kirchoff's Law

$$\epsilon_{\perp} = 1 - R_{\perp} \tag{3a}$$

$$\epsilon_{\parallel} = 1 - R_{\parallel} \tag{3b}$$

The emissivity is thus a function of viewing angle, of wavelength, and of polarization.

Layered Surfaces

The next stage of complication beyond the above case is probably a layered material with the layers parallel to the surface. Equations relating the reflectivities of such materials with the optical properties of the layer substances are contained in the book by Heavens (1955). Thin film optics are still receiving considerable study due to the great interest in reflection and transmission filters of varying types. However no experimenter has seen fit to apply any of the corresponding equations to the planetary observations.

Rough Surfaces

One of the most vexing problems in planetary spectroscopy is the transition from the simple, but generally inapplicable, cases above to the complex, and realistic rough surfaces. For obtaining information about the surface the theory should relate the properties of the scattered light to those of the surface. The former includes both intensity and polarization as a function of angles of incidence and reflection. For the surface we now have to consider in addition to the dielectric properties the surface roughness, presumably expressed in some statistical manner. Unfortunately, the complexities introduced by the surface have forced investigators to make various simplifying assumptions to make the problem tractable.

Although in general the scattering coefficient for a particular polarization is a function of the spherical polar angles of both the incident direction and the direction of observation, it is customary to assume that it depends only on the zenith angles of the two directions and their difference in azimuth angle, A. In effect, this assumes that the scattering is symmetrical about the incident direction. The same assumption is generally made in the formulation of phase functions for particle scattering and may be expected to be valid so long as the sample of randomly oriented scattering centers is large.

While the theoretical aspect of rough surfaces is unsatisfactory, much information has been obtained from comparison of observed emissivities and reflectivities with those of terrestrial materials. The comparison is quite straightforward except perhaps when one wants to translate from reflectivities to emissivities. Such a situation can arise since it is frequently more convenient to make a laboratory measurement of the reflectivity although the planetary observable is the emissivity (more precisely the deviations of the observed emitted radiation from a single black-body curve). In such a case Peake (1959) has shown that the simple form of Kirchoff's Law, equation 3, has to be replaced by

$$\epsilon_{\perp}(\theta) = 1 - \int [R_{\perp\perp}(\theta, \theta', A) + R_{\perp\parallel}(\theta, \theta', A)]\, d\Omega' \tag{4a}$$

$$\epsilon_{\parallel}(\theta) = 1 - \int [R_{\parallel\parallel}(\theta, \theta', A) + R_{\parallel\perp}(\theta, \theta', A)]\, d\Omega' \tag{4b}$$

The reflection coefficients are defined by

$$I_{\perp, REF}(\theta)\, dS\, d\Omega = I_{\perp, INC}(\theta')\, R_{\perp\perp}(\theta, \theta', A)\, dS\, d\Omega' \tag{5a}$$

$$I_{\parallel, REF}(\theta)\, dS\, d\Omega = I_{\parallel, INC}(\theta')\, R_{\parallel\parallel}(\theta, \theta', A)\, dS\, d\Omega' \tag{5b}$$

$$I_{\parallel, REF}(\theta)\, dS\, d\Omega = I_{\perp, INC}(\theta')\, R_{\perp\parallel}(\theta, \theta', A)\, dS\, d\Omega' \tag{5c}$$

$I_{\perp, REF}(\theta)\, dS\, d\Omega$ is the flux of radiation, polarized perpendicular to the plane of reflection, and reflected by the surface element dS into the solid angle $d\Omega$ at the angle of reflection θ ; $I_{\perp, INC}(\theta')\, dS\, d\Omega'$ is the flux of radiation, polarized perpendicular to the plane of incidence, and incident on the element of surface dS at the angle θ'. For temperature measurements where the polarization components are not measured separately the average emissivity, $\epsilon = \frac{1}{2}(\epsilon_\perp + \epsilon_\parallel)$, is the quantity of interest:

$$\epsilon(\theta) = 1 - \int R(\theta, \theta', A)\, d\Omega' \tag{6}$$

The majority of the theoretical approaches to the interpretation of the visible observations have been summarized briefly by Minnaert (1961) in his detailed examination of lunar photometry. Of the equations which have been proposed and used for various purposes two have attracted the most attention. These are

$$\text{Lambert's Law: } R(\theta, \theta') = R(0, 0) \cos\theta \cos\theta' \tag{7}$$

$$\text{Lommel-Seeliger Law: } R(\theta, \theta') = 2R(0, 0) \frac{\cos\theta \cos\theta'}{\cos\theta + \cos\theta'} \tag{8}$$

The former is found to hold empirically for many rough, highly reflecting surfaces; the latter is the asymptotic solution for scattering by a semi-infinite plane material with isotropic scatterers whose albedo approaches zero. This law will be approximately satisfied by a surface consisting of large $\left(\frac{2\pi r}{\lambda} \gg 1\right)$ opaque spheres.

These and other early formulae have not been very successful when applied to the lunar surface, the most intensively studied of all. A new attack on this problem has been undertaken by Hapke (1963) with considerable success. His surface consists of randomly oriented, widely dispersed, opaque particles which backscatter predominantly. The particles must be large enough that diffraction effects are unimportant and the shadows cast are sharp. The ability of the radiation reflected through an angle of 180° to escape without further attenuation is explicitly included in his formulae. The final equations relate the scattered intensity to the individual particle albedo, a, and a parameter g by

$$R(\alpha, \psi, \beta) = \frac{2}{3\pi} b \frac{1}{1 + \cos\psi / \cos(\psi + \alpha)} \cdot \frac{\sin|\alpha| + (\pi - |\alpha|)\cos|\alpha|}{\pi} B(\alpha, g) \tag{9}$$

where
$$B(\alpha, g) = \begin{cases} 2 - \frac{\tan|\alpha|}{2g}\left\{1 - \exp(-g/\tan|\alpha|)\right\}\left\{3 - \exp(-g/\tan|\alpha|)\right\} & \text{if } |\alpha| \leq \pi/2, \\ 1 \quad \text{if } |\alpha| \geq \pi/2, \end{cases} \tag{10}$$

and $\cos\theta = \cos\beta \cos\psi$, $\cos\theta' = \cos\beta \cos(\psi + \alpha)$; ψ and β are the lunar longitude and latitude respectively. The parameter g is approximately equal to $2(\rho/\rho_0)^{2/3}$ where ρ is the apparent density and ρ_0 the density of the particles.

In the past two decades, interest in the theory of electromagnetic reflection by rough surfaces and propagation through random inhomogeneous media has grown. An excellent monograph on the latter subject has been written by Chernov (1960). Careful considerations of the problem of scattering by rough surfaces are due to Rice (1951), Ament (1953), Twersky (1957), and Beckmann (1961 a, 1961 b, 1962). These authors treat a conducting surface whose height is described statistically, paying close attention to satisfying the boundary conditions. Their results are consequently difficult to apply. For our purpose, the more simple and direct approach of Daves (1954) and Clarke (1962) will be more useful in providing insight into the scattering properties of rough surfaces

Clarke (1962) considers a corrugated conducting surface whose mean profile is a plane and whose shape is specified by two parameters, the root mean square deviation of the height above the plane, σ , and the lateral autocorrelation of different elevations. With the assumptions that the plane of incidence is perpendicular to the corrugations, that there is no shadowing and that both the distribution of surface height and the autocorrelation function are Gaussian, he finds the angular power spectrum of radiation scattered from the surface to be given approximately by

$$R(\theta,\theta') = \exp(-\phi_0^2)\delta(S-S_0) + \exp(-\phi_0^2)\sum_{n=1}^{\infty} \frac{\xi_0\sqrt{\pi}}{\lambda}\,\frac{\phi_0^{2n}}{n!\sqrt{n}} \cdot \exp\left\{-\xi_0^2\pi^2(S-S_0)^2/\lambda^2 n\right\} \tag{11}$$

where $\phi_0 = 4\pi\sigma\cos\theta'/\lambda$, $S = \sin\theta$, $S_0 = \sin\theta'$, ξ_0 is the lateral correlation length. The first term is a pure specular reflection which is coherent with the incident radiation; the second term is the diffuse scatter distributed symmetrically about the direction of specular reflection. When ϕ_0 is small, the first term predominates; when ϕ_0 is large, the first term disappears and the second becomes

$$R(\theta,\theta') = (\xi_0/\phi_0)\sqrt{\pi}/\lambda \quad \exp\left\{-(\xi_0/\phi_0)^2\pi^2(S-S_0{}^2)/\lambda^2\right\} \tag{12}$$

Whereas the amplitude of the specular component depends only on σ , the distribution of the diffuse component depends on ξ_0 as well. In this case it depends on just ϕ_0/ξ_0 which is proportional to $\sqrt{2}\,\sigma/\xi_0$, the standard deviation of the slope. With a small mean square slope, the diffuse component decreases rapidly away from the specular direction, even though σ may be quite large.

Extension of this approach to two dimensional roughness should be straightforward, but extension to dielectric surfaces may be more difficult. The assumption of normally distributed heights is probably good. The particular choice of a Gaussian surface autocorrelation function is questionable. This choice is not essential in the theory and the form of the autocorrelation function may be taken as an additional parameter in the theory to be adjusted to give a best fit to observational data. Laboratory tests have shown the first term in equation 11 to provide an accurate description of quasi-specular reflection from rough surfaces (Hendry et al, 1963; Bennet et al, 1961).

A valuable datum not treated in the preceding theoretical approach is the polarization of the received light. The polarization P is defined by

$$P = \frac{\bar{I}_{\perp} - \bar{I}_{\parallel}}{\bar{I}_{\perp} + \bar{I}_{\parallel}} \tag{13}$$

where $\bar{I}_{\perp}$ and $\bar{I}_{\parallel}$ are the intensities of the components polarized perpendicular and parallel respectively to the plane of vision. The plane of vision is in turn defined for reflection by the three points - sun, scattering center, earth. The simple definition has proved satisfactory since the light scattered from the planets has been found to be in almost all cases polarized perpendicular or parallel to this plane (Dollfus, 1961).

Clouds

The natural starting point for a consideration of the optical properties of clouds is the monograph of van de Hulst (1957). He starts with the assumption that the particles in the cloud, or molecules in the gas, are sufficiently far apart that they may be considered as independent scatterers. Then the total scattering effect can be calculated by summing without regard to phase the intensities of the radiation scattered by the individual centers. In his book the complications introduced by multiple scattering are touched on only briefly. Since it would be both presumptuous and pointless to dwell at length on a subject already so well treated we will mention only a few results which are of particular significance for this review.

An important limiting case is Rayleigh scattering which applies if the largest dimension, 2r, of the scattering particle satisfies the conditions

$$2\pi r << \lambda \tag{14}$$

and

$$2\pi r << \lambda/\ldots \tag{15}$$

If the polarizability, p, of the particle is a scalar and is real (a spherical isotropic particle with no absorption) then the scattered intensity for unpolarized incident radiation is given by

$$I_{\perp} = \frac{2^3 \pi^4}{\lambda^4 d^2} \rho^2 I_0 \tag{16}$$

$$I_{\parallel} = \frac{2^3 \pi^4}{\lambda^4 d^2} \rho^2 I_0 \cos^2 \alpha \tag{17}$$

in which d is the distance between the scattering center and the point of measurement. The intensity of forward scattering equals that of backward scattering, and the polarization is positive, ranging from 0 at angles of 0^o and 180^o to 1 at 90^o. When the scattering particles are anisotropic in the refractive index or are nonspherical the induced dipole moment is no longer colinear with the inducing field, so that the polarizability is a tensor. When the scattering function is averaged over all possible orientations of the scatterer it is found that the polarization is decreased and is no longer 1 at 90^o. The scattering diagram for the total intensity becomes more nearly isotropic.

As the particle size increases, the basic criterion for Rayleigh scattering, that the electric field is uniform throughout the particle, is no longer satisfied. Then one enters the realm of Mie theory, which is strictly applicable only for spheres. This has been treated at length by van de Hulst in his excellent monograph. The wild gyrations in the scattering diagrams which result are illustrated in Fig. 4 taken from van de Hulst. The range of particle sizes generally present in a cloud will tend to smooth out the oscillations, producing an average scattering diagram with an intensity maximum in the forward direction. The preponderance of forward scattering increases as the particle size increases. For this type of scattering the polarization can be positive or negative, depending on the wavelength, particle size and refractive index.

As the particle size increases to the point where $2\pi r \gg \lambda$ and $2\pi r (n-1) \gg \lambda$ the complexities of the Mie theory can generally be disregarded and the scattering properties calculated using a combination of geometrical and physical optics (van de Hulst, 1957). Thus the scattering in the forward direction (Fraunhofer diffraction), in the backward direction (the glory) and at the angles of the rainbows is calculated using physical optics. The intensities at other angles follow from geometrical optics taking account of the phase. This approach can provide heightened physical insight into a specific problem and enable a selection of particles to be studied without resorting to the more complex Mie theory.

The total intensity scattering diagram for a large water drop with $2\pi r = 30\lambda$ is shown in figure 5 (Bricard, 1943). The lower solid curve is the contribution by reflection and refraction as calculated by Wiener. The upper solid curve is the total scattered radiation after the diffracted intensity has been added. It is noteworthy that the scattering diagram remains highly asymmetric with forward scattering predominant. Diffraction produces a strong narrow forward lobe, but reflection and refraction also produce a net forward scattering which is very broad; the backward scattering is relatively isotropic. The polarization is positive with a maximum of 0.005 for $\alpha < 8^\circ$, above 8^o it is negative with a minimum of - 0.03 at $\alpha = 25^\circ$.

Absorption, when present in the scattering particle, adds another degree of complexity to the calculations. However, this must inevitably be an important factor for interpreting infrared measurements, and in fact may well prove to be the most valuable tool for analyzing planetary clouds because of the specificity of infrared absorption. Numerical calculations of scattering diagrams have been carried out for a range of particle sizes, wavelengths and complex refractive indices. The work prior to 1957 has been referenced by van de Hulst. Since then only a few further computations have been made (Deirmendjian et al, 1961; Giese, 1961).

Incorporating the scattering properties of individual particles into calculations of the optical properties of clouds falls in the domain of radiation transfer. The definitive treatise of Chandrasekhar (1950) forms the basis of modern usage of the theory. The results which are particularly pertinent to planetary work have been extracted and discussed by van de Hulst (1952) and Harris (1961). Goldstein (1960) has developed equations for the infrared reflectivity of a planetary atmosphere. The results are valid when the extinction due to absorption is much greater than that due to scattering. Averaging over absorption bands consisting of lines is permitted in the theory. It has not been applied to a specific planetary problem.

A very useful simplifying observation has been made by Lyot, and discussed by van de Hulst (1952), for the polarization properties of reflected radiation from clouds. Lyot observed experimentally that the polarization vs. phase angle curve for a system of scattering centers has a form (i.e. relative intensity and sign) nearly independent of concentration. As the concentration is increased multiple scattering increases, but it merely adds an almost depolarized intensity to the polarized intensity resulting from single scattering. This approximation of the form (but not the magnitude) of the polarization to that for a single particle has been confirmed theoretically for Rayleigh scattering (van de Hulst, 1952). Clearly this can be valuable in obtaining particle parameters from polarization measurements.

An important problem for planetary atmospheric analyses is that of line formation in a scattering atmosphere. For a semi-infinite atmosphere of isotropic scattering particles and an albedo which is close to 1 and constant over altitude for a given wavelength van de Hulst (1952) has derived an approximate relation for Chandrasekhar's H function. This leads to the following equation for the fractional absorption, $S_\nu = (I_{CONT} - I_\nu)/I_{CONT}$ (Chamberlain et al, 1956).

$$S_\nu = 3^{1/2}(\mu + \mu_0)\left(\frac{\kappa_\nu}{\sigma}\right)^{1/2} \tag{18}$$

Here μ and μ_0 are the cosines of the zenith angles of the emerging and incident radiation respectively, κ_ν is the mass absorption coefficient and σ the mass scattering coefficient. Chamberlain and Kuiper used this equation in analyzing near infrared bands of Venus. To our knowledge no other theoretical studies of absorption line formation in scattering atmospheres have been applied, despite the importance of the problem and the limited validity of some of the assumptions, particularly that of isotropic scattering.

II. The Radiometric Determination of Planetary Temperatures

Planetary temperatures can be determined in a variety of ways. Of immediate interest to the present review are those techniques for which the measured quantities are intensities of radiation emitted by the planet, thus excluding temperatures derived for example from molecular band analyses. Since our interest is the study of planetary surfaces and clouds the temperatures are less than 1000°K and the peak of the blackbody emission curve occurs in the infrared beyond 2.9 μ. At the upper end of this wavelength range the reflected solar radiation is superimposed on the emitted radiation. Accordingly all temperature measurements are made at longer wavelengths where the reflected solar radiation is insignificant. These fall into two distinct areas - the infrared near the blackbody maximum, and the microwave, well out on the blackbody tail.

The techniques of planetary temperature measurements have been examined by de Vaucouleurs (1954). There are two approaches which have been followed - one measures the ratio of the received energy for two different wavelength bands and compares it with that calculated on the basis of the blackbody equation. The temperature which provides the best fit is then the desired value. This method is very sensitive to errors introduced in evaluating the effects of attenuation by the Earth's atmosphere and to wavelength variations in the planet's emissivity. For this reason it has been discarded in favor of the absolute intensity method.

The absolute intensity method requires a measurement of the planetary emission in a known wavelength band and proceeds from this to the temperature. If the entire spectrum were detected with a uniform sensitivity the Stefan-Boltzmann Law, Intensity $\propto T^4$, could be used. In practice only narrow regions are used, most commonly 8 - 13 μ, and the exponent of T will differ from 4, the actual value depending on the instrumental sensitivity (including atmospheric transmission) and the temperature of the planet. However it remains high in this part of the infrared region since the peak of the blackbody curve is very close. At the peak itself the intensity varies as T^5. The advantage of the absolute intensity method is that the large exponent of T makes the percentage error in the derived temperature much less than that in the intensity. Thus an error of 50 per cent in the intensity due, for example, to an improper estimate of telluric absorption or to a planetary emissivity lower than 1, will affect the temperature by only ca. 14 per cent if the intensity measurement is made near the peak of the blackbody curve.

One of the most important steps in the reduction of the data is the calculation of telluric absorption. This point has been examined by Sinton and Strong (1960) in the course of their radiometric work on Venus and Mars. They noted that the assumption by previous workers that the telluric transmission has an exponential dependence on the air mass penetrated is very crude. A better fit, at least for the 8 - 13 μ region, is a square root dependence, i.e. Transmission = $1 - m \sec^{1/2} Z$, where Z is the zenith angle and m is a constant determined from lunar observations. It is an interesting observation that the temperatures derived using the more advanced instrumentation and reduction of data are within 5 - 10^{o}K of the older results based on the absolute intensity method. This is no doubt a testimony to the quality of the earlier work, but is probably also an expression of the insensitivity of the temperatures to the absolute infrared intensities.

In the microwave range, measurements are made in a relatively narrow band and in the long wavelength tail of the blackbody intensity law. In this case the radiation temperature is proportional to the intensity and whatever errors occur in measurement of the intensity appear directly in the derived temperatures. In the following discussions, the errors in temperature stated by the experimenters will always be given. These will be seen to be large relative to the corresponding errors in the infrared measurements for the reasons stated above. They are also large because, despite the great sensitivity of the radio receiving equipment used, the low intensity of thermal planetary radiation at microwave frequencies gives small signal-to-noise ratios.

Accounting for telluric absorption, on the other hand, is a simple matter because the absorption is small. Correction is made by measuring the planetary radiation as a function of zenith angle and extrapolating to zero air mass using the equation Transmission = $\exp(-\tau_0 \sec z)$ where τ_0 is the normal optical depth.

III. The Moon

A complex of several factors has made the moon an object of great topical interest. The recent rapid advances of radio astronomy, both active and passive, have produced completely new results not obtainable previously. The advent of space probes to permit new observations such as views of the back side and the magnitude of the lunar magnetic field (or better, the absence of one) provided an added spur. Finally the forthcoming opportunity to test theories and interpretations of data by soft-landers and manned exploration heightens the interest still further. As a result several excellent studies of the moon have been published in the last few years. Here we will be content with extracting the highlights from the detailed works, reviewing new data and relating the conclusions reached using the various observational techniques.

In addition to the article on "Photometry of the Moon" by Minnaert in Planets and Satellites (Kuiper et al, 1961), the volume contains several other articles on electromagnetic observations of the moon: "Photometry of Lunar Eclipses" by D . Barbier, "Photometry and Colorimetry of Planets and Satellites" by D. L. Harris, "Polarization Studies of Planets" by A. Dollfus, "Planetary Temperature Measurements" by E. Pettit, "Recent Radiometric Studies of the Planets and the Moon" by W. M. Sinton, and "Radio Emission of the Moon and Planets" by C. H. Mayer. Öpik's chapter on the moon in Vol. I of Progress in the Astronautical Sciences (Singer, 1962) contains a short section on lunar photometry. The pertinent chapters in Physics and Astronomy of the Moon (Kopal, 1962) are "Photometry of the Moon" by V. G. Fessenkov, "The Polarization of Moonlight" by A. Dollfus, "Lunar Eclipses" by F. Link, "The Luminescence of the Lunar Surface" by W. M. Sinton and "Radio Echo Studies of the Moon" by J. V. Evans. Two chapters of Baldwin's (1963) monograph are devoted to the nature of the lunar surface materials as determined by visual, infrared and radio frequency observations.

Visible Region

The subject which has received the greatest attention is the unusual photometric behavior of the lunar surface in the visible region. To set up the problem we will write the reflectivity as

$$\pi R(\theta, \theta', \alpha) = \pi R_o f(\theta, \theta', \alpha) \tag{19}$$

where α is the phase angle. This form is chosen in keeping with Minnaert's equation involving the radiance factor ρ and our previous definitions. The quantity πR_o (Minnaert's ρ_o) is the brightness of a surface element at normal incidence and reflection as compared to that of a perfectly white screen obeying Lambert's Law at normal incidence and the same position. It is called the normal albedo. The function $f(\theta, \theta', \alpha)$, the photometric function, is normalized such that $f(0, 0, 0) = 1$.

For future reference we will define and discuss other terms used in discussing the photometry of surfaces. We will define the albedo as the fraction of light, incident on a surface element whose average surface is a plane, which is reflected into the hemisphere. It will in general be a function of the angle of incidence. We will then use the word by itself for the value at normal incidence, and will note specifically when the albedo is for some other angle of incidence. The albedo is important since, not only does it provide information about the nature of the surface, it also indicates the fraction of solar energy incident on the surface element which is absorbed by it. However, since the albedo is wavelength dependent an average albedo weighted according to the energy distribution in the solar spectrum must be used for this purpose. This albedo is called the bolometric albedo. Before leaving the term albedo, we should note that it is equal to the normal albedo for a Lambert surface. This does not hold for other surfaces and a surface like the Moon has an albedo substantially less than the normal albedo.

For work of the type discussed by Harris (1961) the reflected radiation from the entire planet or satellite is observed. The quantity of particular interest is the Bond albedo which is the fraction of solar radiation, incident on the hemisphere, which is reflected. It can be determined by the product

$$\text{Bond Albedo} = p\,q \tag{20}$$

where p is called the geometric albedo and is defined as $\pi R(0,0,0)$, where R(0, 0, 0) is the apparent normal reflectivity of the disk, and q is the phase integral. The latter is obtained by observing the brightness of the sphere over all phase angles and making the appropriate integration. Its value is sensitive to the scattering function of the surface; it can be determined empirically for Mercury, Venus and the Moon, but must be obtained theoretically for the other objects. This follows from the situation that the moon and inner planets are observed at all phase angles whereas the other planets are observed only over a small range. If the surface obeys Lambert's Law then q = 1.50, if it is also a perfect reflector p = 2/3. The Bond albedo itself is important since, when weighted by the solar spectral curve to give the bolometric Bond albedo, it can be used to determine the total amount of solar radiation absorbed by the sphere.

The photometric function, $f(\theta, \theta', \alpha)$, has been studied in detail for a large number of lunar features and exhibits remarkable properties. These are deomonstrated by Fig. 6 which represents observations of Sytinskaya and Sharonov (1952). The abscissa is the phase angle α, where $\alpha > 0$ is before full moon and $\alpha < 0$ is after full moon. The ordinate is the apparent brightness, i.e., πR, the numbers on the curves refer to specific areas on the surface. It is significant that no matter where the object is located on the disk the peak brightness is observed at full moon. Actually it has been noted that a slight shift of a few degrees of the maximum, in the direction of the Sun's culmination, is observed for certain features (Fessenkov, 1962). It has been inferred from the observation that all areas reach their peak brightness at very nearly full moon that the photometric function has the property

$$f(\theta, \theta', \alpha) = 1 \tag{21}$$

if $\theta = \theta'$. The brightness measurements at full moon then give the normal albedo, irrespective of the location of the area on the disk. The variation in the brightness near full Moon is very marked and is most pronounced for the bright rays and some bright craters (Fedorets, 1952). By examining similar objects, Orlova (1956) has constructed scattering indicatrices for the maria and terrae. In these, figure 7, πR is plotted against θ for constant θ' and α. The curves for the maria are somewhat sharper than for the terrae, and both increase in elongation with the angle of incidence. As suggested by Fig. 6 the normal albedos vary considerably, from 0.051 for a spot inside Oceanus Procellarum to 0.176 for the central peak in the crater Aristarchus. Colorimetric studies summarized by Fessenkov indicate the surface to be of a nearly uniform, slightly reddish, tint with only a few exceptions. These observations are consistent with a uniform structure for all areas of the Moon with only the inherent opacity varying.

An additional property of the reflected light of importance is its polarization. The study of the polarization of reflected visible radiation was perfected in France by Lyot and pursued subsequently by Dollfus who has reviewed the subject at length (Dollfus 1961, 1962). The results indicate the various areas of the Moon have similar polarization curves in that the sign of the polarization is constant over the disk for a particular phase angle. However the magnitude, which is constant near full Moon, shows a dispersion near quadrature with the dark areas having the greater polarization, Fig. 8.

The interpretations of the photometric and polarization work have relied basically on empirical comparisons. It was realized quite early that the measured photometric function could be satisfied only by invoking shadows. A variety of surface models were prepared but none gave a satisfactory fit. Of those empirical models which are described by Minnaert (1961) the lichen <u>Cladonia rangeferina</u> seemed the most appropriate. Understandably the corresponding experimenter, van Diggelen, did not propose the surface to be covered with lichen, but preferred the next best fit, a surface pocked with hemi-ellipsoidal excavations.

Recently two theoretical studies have been made which clarify the situation. Warren (1963) has noted that in order to obtain a maximum in the backscattering direction out to the extreme limb, and to give such a sharp backscattering lobe, the scattering particles must be in a very loose 3-dimensional network. The scattering could be due to opaque particles connected by thin rods, or to randomly oriented rods. Membranes such as exist in vesicular rocks are excluded, the structure must be open. The expected structure is likened to Cladonia rangeferina, or to a Tinker-Toy network. Such a structure could be formed by "... sputtering of vesicular rocks by the solar wind."

Roughly similar conclusions were reached by Hapke (1963) in his theoretical examination discussed in part I. The agreement between his formulae and the variation in brightness with phase angle is very good and gives relative densities of 0.15 and less. He obtains an albedo of the individual particles of less than 0.30.

Laboratory photometric work has also been carried out by Hapke and van Horn (1963). They have observed light reflected at 0° and 60° at various angles of incidence for a variety of materials. No powder as such exhibited the correct properties except when the surface albedo was very low, much below that of the lunar surface. But when the powder was less than a critical size (of the order of 15 μ for dielectric powders deposited in air), it formed randomly oriented linear structures, "fairy castles," as a result of electrostatic forces, when sifted onto a surface. For the opaque materials silver and silver chloride (darkened by exposure to ultraviolet light) the reflection curves were remarkably similar to the Moon's. The curves for AgCl, Cladonia rangeferina and the Moon are shown in figure 9. A darkened artificial sponge also exhibited similar photometric properties. On close examination the sponge was seen to have interconnected holes. The conclusion drawn from both the theoretical and laboratory work is that "dust in some loosely-compacted state on the lunar surface is the most reasonable material to expect. ..."

The preceding conclusion concerning the dust seems unnecessarily exclusive in view of the behavior of the sponge, the discussion of Warren, and the production of sponge-like rock surfaces by a different procedure at the Grumman Aircraft Co. (Markow, 1963). At the Grumman Co. an unusual rock froth has been produced which has interconnected holes from millimeters to microns in diameter. The experiment started with a cleaning of the raw material, pumice, at 150°C for 100 hours at a pressure of 10^{-8} mm Hg. A quartz lamp immersed in the pumice heated it to 1550°C, at which point it liquefied and gases were driven off violently. The lamp was turned off and the above structure obtained. No photometric properties of this material have been recorded but the structure suggests they may be similar to the sponge's. Taking into account this work and the previous discussion any conclusion at the present time about the origin of the highly porous surface must be tentative. It may be due to loosely compacted dust formed from micrometeorite impact, to sputtering rock by solar protons, or to outgassing of lava emerging from the interior.

The polarization measurements of Lyot and Dollfus have been compared with those of a variety of terrestrial samples by these authors (Dollfus 1961, 1962). Negative polarization for small phase angles is exhibited by powders consisting of very opaque grains. An increase in the opacity or a decrease in grain size increases the magnitude of the negative wing. On these grounds Lyot and Dollfus concluded that the lunar surface consists of finely divided opaque particles, similar to volcanic ash with an albedo of 0.13, which cover even the steepest slopes on the Moon. There appear to be no polarization measurements of materials possessing a random 3-dimensional net structure of the type favored by Warren, Hapke and van Horn.

In considering the photometric and polarization data together, some authors have decided that the surface consists of pits to explain the former and has a uniform opaque dust layer to explain the latter. No model incorporating these features has been tested, but one might expect that the presence of the dust would have a deleterious effect on the photometric function. It would be very interesting to observe the polarization curve of *Cladonia rangeferina*, dust "fairy castles," Pele's hair, steel wool, synthetic rock froth and other materials having 3-dimensional net structures to see if any of these could satisfy both the photometric and polarization observations on the Moon.

Another type of observation in the visible part of the spectrum is luminescence of the surface excited by solar radiation. The bombardment by solar protons, X-rays and ultraviolet radiation excites a luminescence for certain areas which was first detected during lunar eclipses by Link, and has been verified by Dubois and Kozyrev who detected it in full sunlight by noting the resulting decrease in Fraunhofer line absorption. To date, the phenomenon does not seem to have yielded significant information but this may be due to the experimental problems and attendant uncertainties. For a discussion of the subject and of its potential the reader is referred to the chapter by Grainger and Ring (1962) in Physics and Astronomy of the Moon.

Radar Reflections

Radar echoes were first obtained from the moon in 1946 (DeWitt and Stodola, 1949) at a wavelength of 2.6 m. These echoes were observed to fluctuate considerably in amplitude and were generally weaker than what one would expect from a dielectric sphere composed of typical terrestrial materials. Operating at wavelengths of 16.8 and 14 m, Kerr and Shain (1951) identified two components in the fading, one of the order of seconds and the other of the order of minutes. The latter was found to be correlated with the lunar librations (Browne et al., 1956). These first experimenters interpreted their results assuming that the moon was a "rough" scatterer and that the scattering phase function for each element of surface would approximately follow Lambert's Law or the Lommel-Seeliger law. Examining the doppler spectrum of echoes obtained at 2.5 m in relation to the lunar libration, Evans (1957) concluded that most of the echo came from the near third of the lunar disk. The scattering phase function was quite different from the Lommel-Seeliger law, and, in fact, the power of cos θ which gave a best fit to his data was 30. Similar results had been obtained by Trexler (1958) at 2.0 m. Subsequent observations with short duration pulses at 10 cm. (Hey and Hughes, 1959 and Yaplee et al, 1958) showed very clearly that most of the echo was coming from a small region in the center of the lunar disk. The pulse lengths employed by the early observers were not small compared to the 0.0116 sec delay corresponding to radius of the moon. The returns obtained by Hey and Hughes (1959) employing pulses of 5 μ sec duration exhibit considerable structure. Figure 10 shows a typical return. One can see the sharp leading edge and the rapid fall off of the waveform with several sharp individual echoes appearing above a diffuse background. No echoes are present with a delay greater than about 1 msec. In general, the height of the sharp echo at the leading edge varied from record to record as do the heights, positions, and number of the sharp pulses which follow. The moon appears to possess a number of scattering centers near its center with their relative effectiveness varying with the lunar libration. If the moon were a smooth dielectric sphere, the radar pulse would be returned with little dispersion, resembling the leading part of the waveform of Figure 10.

On the basis of the apparent specular-like reflections obtained by the radar observers, a theory of the lunar radar echoes has been proposed by Senior and Siegel (1959, 1962) in which the moon is treated as a quasi-smooth spherical scatterer. They point out that because the rate of power reflected decreases rapidly as the pulse progresses back along the lunar surface toward the limb, the moon is not at all a "rough" scatterer as it is for visible wavelengths. Furthermore, they note that the echoes in the leading part of the return are only slightly depolarized. Accordingly they suppose that the surface is composed for a number of smooth scattering centers separated by patches of roughness. The individual spikes on the radar records then arise from these centers and the leading spike is a pure specular reflection from the nose of the moon. Whatever smooth scattering center is at the center of the disk is assumed to be larger than one Fresnel zone for the operating frequency and have the radius of curvature of the moon. Then the reflection from it is indistinguishable from that from a dielectric sphere. The power in the initial spike of the return gives the scattering cross section of the sphere $R\pi r^2$, where r is the lunar radius and R is the Fresnel reflection coefficient for normal incidence on a plane dielectric surface, discussed in section I. Although many of the first measurements were made with long pulses, the authors were able to extract this effective cross-section from them by employing the modulation loss concept introduced by Trexler (1958). They obtained values near $0.0004\,\pi r^2$ for all the wavelengths from 2.5 m to 10 cm. From these rather low values they obtained a dielectric constant of the order of 1.08, which suggests that the lunar surface must be extremely porous.

Aside from the uncertainty due to measurement errors of the order of 100 per cent in estimating the cross section, there is a further objection that may be raised to this interpretation. In part I it was pointed out that the specular reflection from a rough surface will be reduced by the factor $\exp(-\phi_0^2)$, a relations that has been demonstrated in laboratory tests (Hendry et al, 1963) in which the specular reflection of 8 mm electromagnetic radiation from a rough water surface was measured as a function of the statistical parameters of the surface. Even with ϕ_0 large very little depolarization is observed. This relation may be applied in the case of the quasi-specular reflection discussed by Senior and Siegel. A value of $\sigma/\lambda \sim 1/8$ at normal incidence is sufficient to reduce the reflected power to 10 per cent of the incident power, so that only a modest roughness compared with wavelength could account for the small observed cross-sections even though the reflected signal did appear to be specular.

With the improved sensitivities of the radars, echoes have been observed from the entire disk. (Leadabrand, et al, 1960; Pettengill, 1960). With a short transmitted pulse, the power received back as a function of range may be plotted in the form of power reflected from the surface as a function of angle of incidence. Figure 11 shows a plot of echo power as a function of the cosine of the angle of incidence (and reflection). This curve, obtained by Pettengill (1960) at 68 cm, is an average of many echoes, so that the individual sharp echoes discussed above are averaged out Two distinct regimes appear: (a) the sharp leading edge which dies out rapidly, and (b) a weak residual part which persists out to the limb varying approximately as $\cos^{3/2}\theta$. Hughes (1961), operating at 10 cm with pulses of 5 μ sec duration, was able to detect only the leading portion of the return and found that his average curve could be fit by the formula $R(\theta) \propto \exp(-10.2\,\theta)$ for $3^\circ < \theta < 14^\circ$. He noted the similarity between this law and the relation $R(\theta) \propto \exp(-10.5 \sin\theta)$ obtained by Pettengill and Henry (1962) for the leading portion of their echoes at 68 cm and concluded that the scattering is approximately independent of wavelength. However, the most recent observations of Pettengill and Evans (1963) at 3.6 cm are distinctly different from their observations at 68 cm and Hughes observations at 10 cm, Figure 12. Further, near the limb the reflected intensity at 3.6 cm is proportional to cos θ rather than cos $^{3/2}\,\theta$ as at 68 cm. These authors also show a curve of polarization of the echo as a function of delay. The percentage of polarization is seen to decrease steadily from 100 to 60 per cent after 3 msec and after that to decrease more slowly to about 45 per cent at the limb.

In addition to the work of Senior and Siegel (1959, 1962), a number of theoretical attempts to interpret the observations have been made to explain the shapes of the curves of $R(\theta)$ and to obtain information about the parameters of the lunar surface from the curves. Hargreaves (1959), employing a theoretical formula of Ratcliffe (1956) and assuming that the autocorrelation function of the surface is Gaussian, obtained the phase function $R(\theta) = \exp(-\theta^2/\theta_0^2)$ which, when fit to the results of Evans (1957), predicted root mean square surface gradients of about 1 in 10 for the lunar surface.

A rather different approach was taken by Brown (1960). He divided the echoes received by Pettengill and Leadabrand into a quasi-specular component and a diffuse component and treated the quasi-specular part by means of ray optics. He divided the surface into mirror-like facets each having the probability of having area l by s given by $\rho(l, s) = [k \exp(-kl)dl][k \exp(-ks)ds]$ and with the maximum facet size decreasing steadily from the center to the limb. By adjusting the parameter k, he was able to obtain an expression that approximately fit the observed "quasi-specular" component. Since, in this model, all reflections from the facets are at normal incidence, the magnitude of the echo is at every instant of its duration proportional to the Fresnel reflection coefficient for normal incidence. He found the best fit to the data yielded a dielectric constant in the range of 1.2 to 1.4.

Daniels (1961, 1963), taking an approach similar to that discussed in the introduction, supposes that the echo is composed entirely of diffuse scattering. He assumes that the surface heights are normally distributed and tries various forms of the surface autocorrelation function in order to fit the data. The root mean square surface height is taken to be very large compared to wavelength. One form of surface autocorrelation function which he investigates is

$$\rho(x) = (1 - kx/\alpha\lambda) \exp(-x^2/L^2) \tag{22}$$

The first factor is dictated by the sharp initial decrease of the echo and the weak persistence to the limb; the second factor was constructed from a map of large scale structure on the lunar surface made by Hayn in 1914 from photographs. Daniels then infers that the root mean square slope of the surface lies between 8° and 12°. As he implicitly assumes the surface to be composed of perfectly reflecting material, he makes no attempt to deduce a value for the dielectric constant of the material.

Employing a Gaussian autocorrelation function, Hagfors (1961), Winter (1962), and Hughes (1961, 1962) obtained phase functions which are essentially Gaussian, similar to that discussed in the introduction. As pointed out by Daniels (1963), Evans and Pettengill (1963) and Hughes (1962), the Gaussian does not provide a good fit to the data Furthermore, it gives a law which is independent of wavelength in contradiction with the results of Evans and Pettengill (1963). For an exponential autocorrelation function, $\rho(\xi) = \exp(-\xi/\xi_0)$, Hughes (1962) obtained the following form

$$R(\theta) = \frac{2\pi \xi_0^2 \lambda^4}{(4\pi\sigma)^4} \left\{ \frac{\cos^7\theta}{\cos^4\theta + \frac{\lambda^4 \xi_0^2 \pi^2}{(4\pi\sigma)^4} \sin^2\theta} \right\}^{-1/2} \tag{23}$$

which provides a better fit to the data. Although it does not appear to have the correct wavelength dependence, one could argue that the statistical parameters of the surface are a function of wavelength. In effect, the radar waves act as a filter, being sensitive only to surface structure that is of the order of the wavelength in size. On the other hand, the exponential form implies a discontinuous surface and is therefore somewhat artificial.

Evans and Pettengill (1963) obtain a value for the surface dielectric constant from the diffuse scattered component at 68 cm. This component, which varies as $\cos^{3/2}\theta$, is responsible for about 20 per cent of the total power reflected. They suppose that the reflection coefficient for the surface may be written $\pi r^2 k g$, where g is a "gain" factor for the backscatter due to the roughness of the moon. In order to calculate g, one must assume the form of the photometric phase functions. They point out that whether one supposes that the diffuse component approximately satisfied Lambert's law or the phase function proposed by Minnaert g turns out to be about 8/3. Using this value, they obtain a dielectric constant of 2.8 (Evans, 1962).

By distinguishing the echo as a function of range, the observer resolves the moon into annular rings. By further resolving the range signals into the spectral components which result from the doppler shifts due to lunar libration, the observer may distinguish the signals reflected from just two points, P and P', on the surface as shown in figure 13. Maps of the lunar surface have been made in this fashion by Leadabrand et al (1960) and Pettengill (1960). In this manner, Pettengill and Henry (1962) have found that the lunar crater Tycho has an apparent reflectivity 5 to 8 times its surroundings. No other similar identifications have been published to date.

Unlike the observations of reflected sunlight, the earth-based radar observations provide information only about the back scattering properties of the lunar surface. On the other hand, the relatively longer wavelength radio waves will ignore the fine scale roughness of the moon, and one might hope to obtain information about its larger scale irregularities and bulk surface dielectric constant. With the range of dielectric constants proposed by various observers lying in the range of 1.08 and 2.8, the issue is hardly closed. Perhaps only when differential measurements are made employing radar equipment on an orbiting lunar satellite will positive results be obtained. Until then, the statistical approaches of Daniels and others discussed above may, when extended, prove most fruitful. These will have to take into account scattering from a rough dielectric surface and also the effects of shadowing, at least near the limb. The latter are especially important in the explanation of the visible observations.

Infrared Region

The work using infrared emission to deduce lunar surface temperatures has been treated by Pettit (1961) and Sinton (1961b, 1962b). The extensive work by Pettit and Nicholson at Mt. Wilson has now been supplemented and extended by Sinton at Lowell Observatory. Improved experimental techniques such as more sensitive detectors and a narrow band filter at 8.8 μ in conjunction with a more accurate estimate of the atmospheric attenuation have improved the accuracy of the measurements.

One problem that has been of major interest is the temperature variation of a specific area with phase angle, figure 14, and the variation during an eclipse, figure 15. The general trend of these curves can be calculated in a standard heat conduction treatment, where the boundary condition is

$$\sigma T^4 = I + F_0 \tag{24}$$

and σ is the Stefan-Boltzmann constant, I the solar radiation absorbed by the surface and F_0 the energy flow to the surface from the bulk. The effective emitting temperature is taken to be the infrared temperature. It is assumed that

$$I = \frac{G}{x^2}(1-A)\cos(2\pi t/p) \tag{25}$$

where G is the solar constant, x the distance from the Sun in astronomical units, A the albedo, t the time and p the lunar rotation period. Numerical analysis then gives curves of surface temperature vs. the thermal inertia $(k\rho c)^{1/2}$. These quantities -- k, the thermal conductivity in cal $cm^{-1}deg^{-1}sec^{-1}$, ρ the density in g cm^{-3}, and c the specific heat in cal $g^{-1}deg^{-1}$, are taken to be constant. The results of such calculations are indicated by the curves in the figures. The low values of the thermal inertia can be satisfied by finely powdered rock dust in a vacuum but not by denser materials or by powders in a non-vacuum. Sinton estimates the inertia for such vacuum dusts to be $(k\rho c)^{1/2} = 0.001$

The results, however, are not completely consistent since the thermal inertia derived from a lunation is ca. 0.0023 and from an eclipse only ca. 0.0006. The answer to this important difference is left open by Sinton. In examining the general question an effect has occurred to us which acts in the correct direction and could offer an explanation.

One of the assumptions in the treatment is that the albedo, A, be constant. This is no doubt valid for an eclipse where the angle of incidence varies very slightly, but it is probably not true during a lunation. Pettit and Nicholson in their lunation work determined an average intensity of reflected light by observing the sub-solar point for different phase angles. The averaged, i.e. averaged for different areas of the surface, reflected intensity was 0.24 cal cm^{-2} min^{-1}. With a solar constant of 2.00 cal. cm^{-2} min^{-1} this yields an albedo of 0.12 which is much higher than the visual Bond albedo of 0.067 cited by Harris (1961). Since the Bond albedo is the fraction of solar radiation incident on the sphere which is reflected, it is an average of the albedo for the various surface elements with their respective angles of incidence. The bolometric Bond albedo may well be higher than the visual one due to increased near infrared reflection but will still presumably be less than 0.12. Hence the albedo must show a decrease with increasing angle of incidence. The absorbed solar radiation will then decrease more slowly than $\cos(2\pi t/p)$ of (25). This effect is a possible explanation for the observation (Pettit, 1961) that the emitted infrared radiation varies as $\cos^{2/3}\theta$ when the disk is scanned. This is a slower decrease towards the limbs than the $\cos\theta$ dependence expected for an albedo independent of angle of incidence and emission obeying Lambert's Law. Hence there is reason to think the albedo decreases with increasing angle of incidence. Whether the magnitude of the effect is sufficient to account for the large discrepancy in the derived thermal inertias can be settled only by calculation.

If the above treatment supports the lower thermal inertia of the eclipse work presumably a less impacted material than rock dust would be required. This is particularly true in view of Sinton's observation that the most valid eclipse measurement is an area near the limb, where slopes are being observed. As a result the surface element sees more empty space (the theory assumes it sees a solid angle of 2π) than an element in a valley or other depression. Figure 15 reveals that the associated thermal inertia is less than 0.0006.

Other criticisms of the analysis of the lunation and eclipse data have been raised by Buettner (1963). There is a possibility that infrared transparent materials such as NaCl, KCl and CaF_2 are present on the surface so that the layers beneath the surface contribute to the emitted radiation. The observed temperature would then be lower than the surface temperature at lunar noon and higher at lunar midnight. This seems rather remote although it could apply to specific areas. His second point is that there may be heating in depth if the particles are translucent as he suggests. This seems questionable however since it is doubtful if the photometric properties would be satisfied if the particles have appreciable transmission. Both of these first two effects would cause the apparent thermal inertia calculated by the simple theory to be too high. He also goes into some detail on the thermal variation of k, ρ and c, noting in passing that previous estimates of these dependences were incomplete. Although the foregoing criticisms of the theoretical treatment suggest that the derived results be regarded with great caution, there appears to be little doubt that the thermal inertia must be very low, probably in the range .0001 to .002. This is consistent with the photometric results indicating a porous surface structure.

Other authors have introduced a more complicated model consisting of a substratum with a high inertia overlaid by a dust of low inertia. This was proposed to explain the rate of decrease of surface temperature during the totality of an eclipse being less than calculated on the simple model. However, the measurements are not completely clear on this point (Sinton, 1962b), and furthermore, the surface shielding arising from roughness would have this effect. In light of the preceding remarks we concur with

Sinton in his feeling that the present infrared observations do not justify the more complex model.

It is a little surprising that little infrared spectroscopy has been performed on the Moon. Spectra of the moon have been obtained to improve analyses of planetary spectra, e.g., Sinton and Strong (1960a), but seldom for their own sake. Adel (1946) has reported the 8-13 μ spectrum as observed from Earth. Telluric absorption bands were not removed and the data were not calibrated and compared with blackbody curves.

The long wave infrared spectrum can be useful in detecting certain types of rocks providing the surface is not too rough and the albedo not too close to 1. An interesting study of what might be attained under ideal conditions is that of Lyon (1962) who has examined the reflection spectra of a large number of polished minerals.

Microwave Region

Thermal emission at radio wavelengths must arise from layers beneath the lunar surface, and a study of this emission provides information concerning the bulk properties of the lunar surface down to a depth of several centimeters. Since the first single observation of lunar radiation at 1.25 cm by Dicke et al (1946), studies have been conducted at wavelengths ranging from .15 to 75 cm. The results of most measurements made prior to 1961 are reviewed by Mayer (1961) and Sinton (1961). The interpretations of the measurements in conjunction with the infrared and optical studies have led to estimates of the bulk dielectric constant, porosity, electric and thermal conductivity, and heat capacity of the material near the surface. As in the case of the infrared work, results of eclipse observations appear to imply somewhat different values for the parameters than do the results of observations throughout a lunation.

Piddington and Minnett (1949) made the first comprehensive observations throughout a lunation, operating at a wavelength of 1.25 cm with an antenna having a beamwidth of .75°. As a consequence of the large beamwidth, their data represent an average of the emission over the disk. They found the variation of brightness temperature to be very nearly sinusoidal and of the form

$$T = 249 + 52 \cos(2\pi t/p - \pi/4) \tag{26}$$

$t = 0$ corresponds to full moon and p is the lunar period. The maximum was seen to lag the full moon by 45° in contrast to the infrared measurements.

Sinton (1956) reported measurements at 1.5 mm using optical equipment, his beamwidth including the entire moon. He obtained disk temperatures of approximately 120°K near new moon and 336° at full moon. Within the accuracy of his data, they could be said to agree with the infrared results.

Coates (1959) at 4.3 mm obtained contour maps of the lunar brightness at three different phases, 257°, 306° and 100° from full moon, employing an antenna with a half power resolution of 6.7'. His results indicate that the maria heat and cool more rapidly than do the mountainous regions. Such results show clearly the danger in drawing conclusions about the surface composition from measurements with instruments that accept emission from all parts of the disk at once.

Gibson (1958) observed the variation in brightness across the disk at 8.6 mm during a lunation using an instrument with a half power width of 0.2°. With this resolution, he obtained a curve of the central disk brightness temperature that contained many harmonics. The maximum and minimum temperatures were 215° and 145°, and the maximum occurred about half-way between third quarter and full moon.

With increasing wavelength the variation of brightness with phase becomes smaller. Here we present only some typical results, a more complete compilation is given by Mayer (1961). At 3.15 cm Mayer (1961) reports a temperature variation of the form

$$T = 195 - 12(\pm 5)\cos[2\pi t/p - 44^{\circ}(\pm 15)]\,, \tag{27}$$

Zelinskaya and Troitsky (1956), on the other hand, report a temperature of $183 \pm 13^{\circ}$ constant to within $\pm 9^{\circ}$. At wavelengths longer than 3 cm, no phase effect at all has been observed. At 9.4 cm Medd and Broten (1961) report a temperature of 220°, with no phase effect observed. At 21 cm Mezger and Strassl (1959) found a temperature of 250° (within 12 per cent), constant to $\pm 5^{\circ}$ over a lunation, and at 75 cm Seeger et al (1957) obtained a temperature of 185°, constant within 10 per cent. These are typical results.

A number of recent observations made by workers in the USSR in the range of 4 mm to 10 cm have been reported (Kopal and Mikhailov, 1962). The observations at 3.2, 2.0, and 0.8 cm were made with the 22 meter antenna of the Lebedev Institute permitting high resolution, particularly at 8 mm where the beamwidth is 2'. The brightness contours obtained by Salomonovich (1962) at 8 mm during various phases of the moon are shown in Figure 16. These show the phase variation of the central disk temperature to contain many harmonics. They also show very small limb darkening along the equator and the distribution of temperature with respect to latitude, β, to be given approximately by $\cos^{1/2} \beta$. In the absence of appreciable limb darkening, Salomonovich concludes that the bulk dielectric constant for a smooth surface is less than 2. The mean central temperature was found to be 210° ($\pm$ 15 per cent) and the ratio of the amplitude of the first harmonic to the mean 0.20. At 2.0 cm and 3.2 cm the mean temperatures of 190° and 223° respectively were obtained with ratios of fundamental to mean temperature of 0.10 and 0.075 respectively. At 10 cm a constant temperature of 230° ($\pm$ 15 per cent absolute accuracy) is obtained (Koshchenko et al, 1962). Kislyakov (1962) employing an antenna of 25' beam width at a wavelength of 4 mm, obtained the form

$$T = 230 + 73 \cos(2\pi t/P - 24^{\circ}) \tag{28}$$

for the central disk temperature with an absolute accuracy of $\pm$ 10 per cent.

An analysis of the expected emission from the moon has been made by a number of investigators (Piddington and Minnett, 1949; Wesselink, 1948; Jaeger and Harper, 1950; Troitsky, 1954, 1962; Sinton, 1961). These relate the diffusion of the heat into the moon from the surface, which is periodically heated by the sun, and the thermal electromagnetic emission radiated out of the moon. The temperature of the latter roughly corresponds to the temperature of the moon at the level which is at the electromagnetic skin depth, l_e. The following expression (Troitsky, 1962) for the mean value and first harmonic is typical and applies for either single or double layer models.

$$T_e = (1-R)T_0 + (1-R)\frac{T_1}{m_\delta m_s} \cos(2\pi t/P - \xi_\delta - \xi_s) \tag{29}$$

T_0 and T_1 are the mean value and first harmonic of the surface temperature; R is the Fresnel coefficient of the surface (assumed smooth) for normal incidence. The other symbols are defined as $m_\delta = \sqrt{1 + 2\delta + 2\delta^2}$, $\xi = \tan^{-1}\frac{\delta}{1+\delta}$, $\delta = \frac{l_e}{l_T}$, $l_T = \left(\frac{P k}{\rho c \pi}\right)^{1/2}$.

l_T is the thermal skin depth, the depth at which the amplitude of the first harmonic has decreased to e^{-1} of its surface value. δ is the ratio of electromagnetic to thermal skin depth in the substratum and m_s and ξ_s are the quantities corresponding to the above relations for the surface layer. Formulae which include all the harmonics are given by Jaeger (1953) and Sinton (1961), although most of the interpretations have been made using just the mean value and first harmonic.

Because Piddington and Minnett (1949) obtained a phase lag of 45^o, which appears to be the maximum value for a single-layer model($m_s = 1$, $\xi_s = 0$), they concluded that the most probable model consisted of a thin layer of material having low electrical conductivity, low thermal capacity and moderate thermal conductivity overlying another deeper layer for which these parameters are higher. Sinton points out that there is actually an additional 6^o lag in the fundamental wave at the surface (not shown in the formula above) so that a maximum lag of 51^o is possible. He suggests that their results may be fit as well with a single-layer model.

Because of the harmonics appearing in his results, Gibson (1958) compares them with the theoretical calculations of Jaeger (1953). He finds a best fit with a homogeneous model having $(k\rho c)^{1/2}$= .001 and an electromagnetic skin depth of 3.6 cm. This corresponds approximately to the properties of dust, at least in the thermal properties. In interpreting his data, Gibson uses a dielectric constant of 5 so that $1 - R = 0.85$. As pointed out by Sinton, R should probably be somewhat smaller. In reinterpreting Gibson's data, he obtains a skin depth closer to 5 cm.

In principle, knowing T_0 and T_1, from infrared observations, one can find δ and R by measuring the mean and first harmonic microwave temperatures using equation 29. R can be found from $T_0(1-R)$. Mayer (1961) has estimated a value of 0.91 for 1-R from his measurements and hence a dielectric constant of about 3.5, assuming a single-layer model. Although δ is given directly in terms of the phase shift, ξ_δ , inaccuracies in measuring the phase are critical near 45^o where this would require δ to be infinite.

Assuming $(k\rho c)^{1/2}$ = .001 and c = 0.2, Sinton (1961) has derived mass absorption coefficients from the measurements made at the different wavelengths. He finds these values consistent with an electromagnetic skin depth which is proportional to wavelength. Such a dependence is to be expected if the absorption is due to crystal lattice vibrations in the far infrared. The value of the mass absorption coefficient of 2.9 cm^2/g found at 1.5 mm is comparable to values near 2 found for some tektites.

Reviewing the recent Soviet lunation studies referred to above, as well as the other available data, Troitsky (1962) draws a number of conclusions concerning the nature of the lunar surface. Using equation 29 above, he concludes that the data at all wavelengths are consistent only with the single-layer model. In reaching this conclusion he assumes $(k\rho c)^{1/2} = .001$, $c = 0.2$ and $T_0/T_1 = 1.5$ from the infrared data. In agreement with Sinton (1961), he finds l_e/l_T, the ratio of electromagnetic to thermal skin depths, proportional to wavelength, in particular, $l_e = 2\lambda\, l_T$. Thus with $l_T = 10$ cm, emission at 10 cm arises from a depth of 200 cm. This wavelength dependence argues against admixtures of powdered meteoritic iron in excess of 2 or 3 per cent. By making use of a semi-empirical relation which states that the ratio of loss tangent to density is independent of density in porous materials, and by measuring this ratio in some terrestrial materials suggested by Barabashev as likely lunar prototypes, he obtains a dielectric constant of 1.6. From this Troitsky suggests that the density is about 0.5 g cm^{-3} and the porosity may be as great as 80 per cent.

Eclipse observations have been made on a number of occasions at different wavelengths by various observers. The general results are that the observed temperature variations during the eclipse are anomalously small compared to the lunation results. Gibson (1961), observing the total eclipse of March 13, 1960 at 8.6 mm, found no variation in excess of 1°K which was the limit of the detectable signal. Tolbert et al (1961), observing the 25 August 1961 eclipse, obtained a decrease of 10°, employing an antenna having a 0.2° beamwidth. The variation they found during a lunation was from 145° to 260°. These are typical results. One atypical result is the observation of W.C. Tyler and J. Copeland (1960) of the September 1961 eclipse during which they noted a decrease in temperature of 20° at 8.6 mm. On the basis of his eclipse measurements, Gibson (1961) inferred an electromagnetic skin depth of 30-50 cm which is significantly larger than the value of 3.6 cm he had obtained from his lunation study (1958). In order to erase the contradiction, he proposed a two-layer model "with a shallow top layer, somewhat like terrestrial sand covering a porous substratum of high electrical conductivity."

An alternative scheme for explaining Gibson's 8.6 mm eclipse observations would suppose that there is heating in depth by the solar radiation. This is similar to the proposal of Buettner (1963) except that there is also a possibility that the radiation penetrates due to the porosity of the surface structure composed of interconnected holes. The temperature is then essentially uniform to the depth of solar penetration which will be greatest at the center of the disk at full moon.

A study of lunar emission near 10 cm has been made by Cudaback (Bracewell, 1962) employing an interferometer whose beam width was 2.3' by 2.4°. He observed no phase effect and from the absence of equatorial limb darkening concluded that the effective smooth surface dielectric constant lay between 1.1 and 1.5. He observed the latitude variation of temperature to be $\cos^{1/2}\beta$.

There is a definite difference between the parameters of the surface inferred from the eclipse and lunation observations, particularly in the microwave region. This suggests that the simple model consisting of a quasi-smooth homogeneous surface must be modified, perhaps as suggested by Gibson (1958). One factor which has not been given much weight in the various investigations is the surface roughness detected by the radar observers. This roughness will certainly confuse the inference of the dielectric constant from the lack of limb darkening. Troitsky (1962) has proposed a scheme which he feels will provide results which are relatively independent of surface roughness. For this one must use an antenna possessing high resolution and observe the emission during a lunation from selected lunar regions at different longitudes. The effective skin depth seen at each longitude ψ is then $l_e \cos \psi$, and from measurements of the phase lag at these various longitudes one may infer the dielectric constant from the formulae above. The importance of the high resolution studies should be emphasized. The measurements of Coates (1959) and Salomonovich (1962) clearly show that the properties of the various features are different, and therefore observations which average emission from the entire disk may be misleading. Recent observations of the craters Tycho (Sinton, 1962) and Aristarchus and others (Shorthill et al, 1960) in the infrared during eclipse have shown that these do not cool as rapidly as their surroundings, further emphasizing the need for high resolution observations.

IV. Mercury

The planet Mercury resembles the moon in the photometric properties that have been studied. The integrated light has been measured quantitatively as a function of phase and color, and yields a phase integral of 0.563 and a visual Bond albedo of 0.056 (Harris, 1961), Table 1. The comparable quantities for the moon are 0,585 and 0.067. In contrast, the phase integrals and visual Bond albedos of the other planets are all much higher. The polarization (Dollfus, 1961), Figure 8, also resembles very closely that of the lunar surface, further emphasizing the similarity of the two surfaces.

The only infrared measurements have been of the radiometric type (Pettit, 1961). The sensitivity of the detection systems was not sufficient to permit any resolution on the disk. With the assumption that the surface temperature at zero phase has the same variation over the disk as the moon, the subsolar temperature at mean distance from the sun was found to be 613°K.

A variety of approximations and assumptions are present in this number. An asymmetry in the planetary phase function was attributed to mountainous areas on one side of the planet. The thermal radiation encompassed both the 3-4 and 8-13 μ atmospheric windows and a water cell was used to separate the thermal from the reflected radiation. Uncertainties will accordingly be introduced due to the required approximations calculating the telluric attenuation. And, of course, there is the deviation of the surface emissivity from 1, although this will probably not be great and the resulting correction to the temperature only a very few degrees. Infrared radiometric observations of Mercury using modern techniques would provide spatial resolution on the disk in narrow spectral regions where our atmospheric absorption is slight, but it would be surprising if they differed significantly from the Pettit and Nicholson work.

The only reported radio observations are those of Howard et al (1962). Assuming that the surface temperature is proportional $\cos^{1/4}\theta$ (the coordinate axis pointing to the sun) and is zero on the dark side, they infer a temperature of $1100° \pm 300°$ for the subsolar point. Figure 17 shows their results at various phase angles. The solid phase curve represents the infrared observations of Pettit (1961). Although the microwave temperatures appear significantly higher than the infrared temperatures, the authors do not feel that the difference is significant. They do suggest that, if it is real, radioactive heating from within might be responsible. In any case, further measurements should be made at both shorter and longer wavelengths and over larger phase angles to resolve this point. That such measurements have not been reported to date attests to their difficulty.

Kotel'nikov et al (1962) have reported radar contact with Mercury at 43 cm. Although the signals were weak, they established a reflectivity of

3-6 per cent assuming an "isotropically scattering surface," a result comparable to that of the moon.

V. Venus

Visible and Near Infrared

Photometric studies show the reflectivity to increase towards the red, Table 1 (Harris, 1961), in harmony with the visual observation that it has a definite yellow tint. The source of the increased absorption in the blue has been attributed to the cloud particles rather than to gaseous components (Öpik, 1962a). Three arguments for this have been advanced. The first starts from the ultraviolet photographs of Ross which reveal dark bands near the equator and roughly perpendicular to the terminator, and bright areas near the cusps of the crescent. If the absorption were due to gaseous components an unnatural atmospheric circulation would be required, rising at the "poles" and descending at the equator, resulting in a higher cloud level at the poles. The second argument is the failure to detect absorption lines which one would expect if the absorption were due to rotation-vibration-electronic bands of the gas molecules. The smoothly varying absorption, on the other hand, is characteristic of most materials in condensed phases. Finally, photometry across the disk has been carried out for phase angles near 90°, showing brightening toward the limb, and the analysis indicates the absorption is due to the cloud material. The results of Öpik's analysis were not very definitive in selecting a best cloud-gas model. He notes that to obtain more positive deductions "...a complete spectrophotometric survey of the disk of the planet in different colors, extending over a wide range of phase angle and based on photographs of the highest possible resolving power, is needed."

The nature of the absorbing particles is still unsolved. Öpik states their reflectivity is similar to that possessed by many powdered materials including sand and sodium carbonate. This is not quite correct since silica, the major constituent of sand, and sodium carbonate are both colorless and appear white when finely divided. If the color is due to inorganic materials it must be supplied by other components such as iron oxides. Sinton (1953) has suggested that polymerized carbon suboxide is the absorbing material, although no absorption lines of monomeric C_3O_2 or of the O_2 evolved in the synthesis from CO_2 had been observed (Sagan, 1961; Öpik, 1961). Recently, Prokof'ev (1962) has reported observing O_2 on Venus, lending support to Sinton's suggestion.

Polarization measurements have also provided valuable data on Venus. The visible polarization curve as obtained by Lyot (Dollfus, 1961) is shown in Fig 18. Laboratory experiments did not give a good duplication of the observed curve although there were similarities in form with the polarization curve of 2.5 μ diameter water drops. Other possibilities for explaining the polarization curve have been raised by van de Hulst (1952). He noted the similarity of the first polarization maximum to that of a rainbow and suggested by analogy that 5-10 μ diameter quartz particles could be responsible. The idea that the clouds may not be water drops or ice particles was strengthened by Kuiper's (1957b) near infrared polarization measures which were not in accord with water drops. An interesting wavelength dependence of the polarization has been found by Gehrels (1959). Towards the ultraviolet the polarization increases; at a phase angle of 59^{o} it is -1.7 per cent for visible and + 2.4 per cent for ultraviolet radiation. Öpik (1962a) has ascribed the change to an increased contribution of Rayleigh scattering from the atmosphere above the clouds. Assuming the polarization of the clouds is independent of wavelength he deduces from observations of Gehrels at a phase angle of 90^{o} that the mass of atmosphere over the clouds is 40 g/cm^2. He observes that "...the estimate of the atmospheric mass greatly depends on the assumed value of the negative polarization of the clouds, and may easily be doubled." However, if the albedo of the cloud particles decreases in the ultraviolet their polarization will increase in the positive direction. This would act to decrease the positive contribution of the atmosphere and accordingly lower the derived air mass above the clouds.

Deriving the various atmospheric parameters from the photometric and polarization data now available is clearly difficult. The conclusions would be much less ambiguous if a photometric study such as that suggested by Öpik were undertaken in conjunction with polarization measurements at various wavelengths.

Another potentially valuable approach is a detailed analysis of the CO_2 absorption bands in a manner similar to that of Chamberlain and Kuiper (1956). They assumed isotropic scattering and obtained a relationship between the fractional absorption and the ratio of the mass absorption coefficient to the mass scattering coefficient. This they used to obtain a temperature from the intensity distribution of the rotational lines. It would be interesting to see if the calculated results are sensitive to the form of the scattering function, since they might then be used to deduce properties of the clouds as well as of the gas present in them.

In the photometric near infrared observations have been made out to ca. 3.8 μ by Kuiper (1947, 1952, 1962), Sinton (1962c) and Moroz (1963a, 1963b). Sinton noted a step-wise decrease in the albedo towards longer wavelengths and felt this may be due to water in the form of ice crystals in the clouds. He used his albedo measurements together with shorter wavelength albedos obtained by himself and coworkers to calculate a bolometric Bond albedo of 0.73. The suggestion that ice particles may be present in the clouds has not been confirmed by either Kuiper, fig. 19, or Moroz, both of whom had spectra superior in resolution to Sinton's. In fact they note the absence of specific absorption features of ice particles and concluded that the clouds must consist of a substance other than ice. From his albedo measurements, taking account of CO_2 absorption, Moroz has calculated a bolometric Bond albedo of 0.66. For the origin of the albedo maximum between 0.65 and 1 μ he accepts a proposal by Rozenberg that it arises from an optically thin cloud layer, consisting of 2 μ diameter particles over a weakly reflecting surface. His statement that this is in agreement with Lyot's work is incorrect since Lyot considered only water drops, and Moroz has rejected this possibility. An alternative explanation is that there is an absorbing constituent of the clouds causing the decreased albedo. The dust which Moroz feels may constitute the cloud material could well contain the necessary materials.

In this context Kaplan (1963) has proposed that the clouds consist of condensed hydrocarbons or other organic compounds. Such compounds would absorb strongly in the 3-4μ region and could, in conjunction with the CO_2, provide a greenhouse effect sufficient to raise the surface temperature to the ca 600^o K observed in the microwave region. This proposal should be accepted with some reserve since we would expect the organic compounds to be more strongly colored than the Venusian clouds, and since no resolved CH stretching bands have been observed in the 3-4 μ region. Experience indicates that a featureless broad absorption in this region occurs only if a wide range of CH types exists, and this in turn suggests the presence of strongly colored compounds.

Infrared

Radiometric measurements have now been carried out by several investigators over a period of many years. The earlier work in the 8-13 μ window is reviewed by Pettit (1961) and Sinton (1961). This work established several important features: 1) the temperature at the sub-Earth point is 233 - 240°K, nearly independent of phase; 2) limb darkening exists and approximately obeys a $\cos^{1/2}\theta$ law; 3) the temperature at the poles is 20-25°K less than at the equator, even after the limb darkening has been factored out. The terms "equator" and "poles" are used as if Venus had a rotational axis perpendicular to its orbital plane.

Recently, using an interference filter to isolate a well-defined band in the 8-13 μ window and a mercury-doped germanium photoconductive detector, Murray et al (1963) have used the 200 inch Mt. Palomar telescope to record the thermal emission of Venus. Because of improved sensitivity they were able to use a diaphragm only 1/30 the diameter of the disc. The bilateral symmetry of the emission was confirmed, although the equator to pole variations appears to be only about 1/2 that found by previous workers. The most interesting aspect of their work is the 207°K temperature obtained for the center of the disc. Not only is this considerably lower than the value found by previous workers, it is also considerably lower than the calculated radiation temperatures which themselves should be lower than for the sub-Earth point. These temperatures are 234°K for a bolometric Bond albedo of 0.73 (Sinton's value) and 264°K for the albedo of 0.59 favored by Öpik. The discrepancy between the new, and presumably more accurate, sub-Earth temperature and the older values, which are in relatively good agreement with the radiation temperature for a bolometric Bond albedo of 0.78, has not been resolved. Murray believes that subsequent temperature determinations of the Galilean satellites of Jupiter have shown that any experimental corrections necessary would decrease the Venus temperatures, increasing the discrepancy.

A resolution of the problem by recording thermal emission in other parts of the infrared, and by repeating existing radiometer and albedo work, is a prerequisite for any reliable atmospheric model. In fact Sinton (1962c) has observed an emission at 3.75 μ which corresponds to a temperature of 236°K, in agreement with the older work. The advent of balloon astronomy permits a considerable extension of this radiometer work so that a solution is hopefully not far off.

The limb darkening in the earlier measurements has been examined by Sinton using the theoretical treatment of King (1956) for radiative equilibrium of a line-absorbing atmosphere. He was unable to distinguish between this and a gray atmosphere. The agreement between the observed limb darkening curve and those calculated was poor for the semi-infinite atmospheres and suggested "...that the part of the atmosphere in radiative equilibrium is not optically thick but has a finite thickness greater than 1." This followed from the fact that the calculated curves showed a darkening greater than $\cos^{1/2}\theta$. This observation could also be explained by a lower altitude for the clouds towards the limbs. Such a mechanism has been advanced to account for the nearly uniform 8-13 μ temperature for the illuminated and the dark regions (Sagan, 1961). Whatever the reason for the exact form of the limb darkening, its presence shows the temperature to be decreasing with altitude in the atmospheric region where the detected 8-13 μ radiation originates.

The infrared radiometer measurements from the Mariner fly-by in 1963 are in agreement with the older data (Chase et al, 1963). Observations in two channels, 8.1 - 8.7 μ and 10.2 - 10.5 μ, gave the same temperatures, which were "...on the order of 240°K" at the center of the disk. The light- and dark-side temperatures were similar and limb darkening was observed. An anomalous area, 10°K colder than the surroundings, was detected near the south pole.

Spectral resolution in the 8-13 μ region has been obtained for Venus, with the sacrifice of any spatial resolution. The initial reduced spectra of Sinton and Strong (1960b) indicated an effective black-body temperature of 220-230°K, with a minimum in the energy curve at 11.2 μ. Kaplan (1961) has reanalyzed the data and obtained a smooth curve with a uniform effective temperature of 225°K. If the 11.2 μ band is real and not just a result of imprecise data reduction it may be indicative of the presence of inorganic carbonates in the clouds (Rea, 1963). Such materials have been proposed by Öpik (1962a) as atmospheric components in his aeolosphere model. As noted before they could also act to produce a greenhouse effect.

Passive Microwave Observations

Venus has undoubtedly received more attention from observers at radio wavelengths than any of the other planets. At inferior conjunction it presents a disk nearly 1 minute in diameter and its radiation is relatively easily detected by instruments employing conventional receivers. It was first observed by Mayer et al (1958) in 1956 at a wavelength of 3.15 cm, at which time an effective disk temperature of $595^\circ \pm 55^\circ$ was obtained. This result was rather startling, and at each inferior conjunction following this an increasing number of experimenters has obtained further observations at wavelengths ranging from 4 mm to 40 cm. Results obtained prior to the inferior conjunction of November, 1962, have been reviewed by Mayer (1961) and Roberts (1963).

The results of observations taken near the November 1962 conjunction are shown in Fig. 20 along with some results obtained earlier. Both the 4.0 mm (Kislyakov, 1962) and the 4.4 mm (Grant and Corbett, 1962) data were obtained in 1961. The value of $315^\circ \pm 70^\circ$ reported by Kuz'min and Salomonovich (1960) at 8.0 mm is also shown, although a value of $374^\circ \pm 75^\circ$ (Kuz'min and Salomonovich, 1963) was obtained by the same workers at the 1961 inferior conjunction. The value of $395^\circ \pm 30^\circ$ shown at 8 mm represents an average of results obtained by several parties, three during the 1962 inferior conjunction: $374^\circ \pm 75^\circ$ (Kuz'min and Salomonovich, 1963); $360^\circ \pm 100^\circ$ (Copeland, 1963); $410^\circ \pm 40^\circ$ (Gibson, 1961); 380°, +55, - 75°(Lynn, 1963); $394^\circ \pm 70^\circ$ (Thornton and Welch, 1963). The next three values shown were obtained near the 1962 inferior conjunction: 395°, + 75°, - 55° at 1.18 cm (Staelin et al, 1963); $520^\circ \pm 40^\circ$ at 1.18 cm (Gibson, 1963); and $528^\circ \pm 127^\circ$ at 2.07 cm (a preliminary result of McCullough, 1963). The 3 cm results had been obtained previously by workers at the Naval Research Laboratory on several occasions (Mayer, 1961). The temperatures at 19 cm, 21 cm, and 40 cm are those reported by Drake for observations near the 1962 conjunction (Drake, 1963). The 10 cm and 21 cm data are in fair agreement with earlier results (Lilley, 1961). The 40 cm results are new.

One of the most interesting of the new results is the temperature of $502 \pm 40^\circ$ found by Gibson at 1.18 cm. This high value indicates there is no more than a trace of water in the entire Venus atmosphere, for otherwise the 1.18 cm temperature would be the same as or lower than the 8 mm temperature (Barrett, 1961). This is in harmony with the near infrared cloud observations discussed above and with past attempts to find H_2O vapor by detecting its absorption (cf Rea, 1962, for a discussion of this work). However recent work reported by Dollfus (1963) using a broad-band photometer at 1.4 μ gives an abundance of 7×10^{-3} g cm^{-2} above the effective cloud level. This value, which would be further increased if the effective pressure in the absorbing path length is less than 1 atmosphere, is anomalous in view of the other results. If Dollfus' value is in error it may be due to an incomplete compensation for the Venusian CO_2 absorption.

High resolution scanning of the Venusian disc has been carried out by three groups of investigators. The microwave radiometers on the Mariner II fly-by spacecraft gave 1.9 cm temperatures consistent with those in Fig. 20 and also, more significantly, gave definite evidence of limb darkening (Barath et al, 1963). Clark (1963) used the two element interferometer of the California Institute of Technology at 10 cm. He obtained an interferogram which was sufficiently extensive to suggest that Venus at this wavelength is probably not a uniformly bright disk equal in size to its optical disk. His results fit either a uniform disk 15 per cent larger or one of the same size with a bright rim containing 25 per cent of the flux. At 3.02 cm Korolkov et al (1963) have employed the large Pulkovo Observatory radiotelescope which has a rectangular antenna pattern whose half-widths are $1'.2$ and $3'.1$. The data have not been quantitatively analyzed but they show that the radius of the emitting disk is less than 1.07 times the Venus radius, and that limb darkening is present.

At least three sets of experimenters have observed Venus through large enough phase angles to detect variations of the planetary brightness temperature with phase angle. Figure 21 shows the data taken by the Naval Research Laboratory experimenters at both 3 cm and 10 cm (Mayer, 1961) and the first 8 mm data of Kuz'min and Salomonovich (1960). Also shown are the 1961 10 cm data of Drake with a least squares fitted sine curve (1962). Both sets of data indicate a small phase effect with the minimum occurring after inferior conjunction. Combining both his 1961 and 1962 observations, Drake (1963) obtained a mean temperature of $622^{\circ} \pm 6^{\circ}$, a periodic component of magnitude $41^{\circ} \pm 12^{\circ}$, and a phase angle of $21^{\circ} \pm 9^{\circ}$ after conjunction for the minimum temperature. The minimum temperature occurring after inferior conjunction argues for slow retrograde rotation, and Drake sets the probability of retrograde rotation at 0.991 in the absence of an implausible meteorology. On the other hand, Kuz'min and Salomonovich (1963), who observed a large phase effect in 1961 at 8.00 mm, found the minimum to occur before inferior conjunction.

Arguing similarly that the radiation they observed was from the surface or lower layers, they inferred that the rotation was direct. The 1962 radar results at the Jet Propulsion Laboratory discussed below, argue strongly for retrograde rotation (Goldstein and Carpenter, 1963).

A number of attempts have been made to explain the high brightness temperature of about 600°K between 3 cm and 10 cm. 600°K is considerably in excess of the infrared temperature of 207-240°K. Jones (1961) proposed that the high emission arises from a dense ionosphere with critical frequency near 1 cm so that the surface or lower clouds at about 350°K would be visible only at the shorter wavelengths. This would require an ionosphere about three orders of magnitude more dense than that of the earth; however available mechanisms for producing such an ionosphere seem quite inadequate (Sagan et al, 1961). Both the Mariner II limb darkening results at 1.9 cm and the low brightness at 40 cm found by Drake (1963) argue against this model. The former implies, in fact, that the higher temperature radiation arises from the surface or adjacent low level atmospheric layers. The limb darkening also contradicts the proposal of Tolbert and Straiton (1962) that the high emission is due to electrical discharges between atmospheric particles.

If one assumes that the surface temperature is about 600°, there remain the questions of how it could be so hot relative to the infrared and radiation temperatures, and what is the explanation of the microwave spectrum.

Öpik (1961) has proposed a model (the aeolosphere model) in which the surface is heated by wind friction due to dense turbulent dust clouds, the heat carried down to the surface from higher levels where the solar radiation is absorbed. The high surface temperature is then due to the great opacity of the dust clouds in the infrared. The decrease in microwave radiation at wavelengths shorter than 3 cm is due to atmospheric absorption by some unspecified gases or particles. Such a model should exhibit little phase dependence of the surface temperature and the phase effect that is observed in the 10 cm radiation (Drake, 1963, 1962), which presumably arises from the surface, tends to argue against this model. The greenhouse effect due to CO_2, the only gas which has been identified positively in the Venus atmosphere, is far too meager (Wildt, 1940.) Sagan (1960) has suggested a model which includes water to provide the long and short wavelength opacity to keep the surface temperature high. However, Spinrad's (1962) estimates of water vapor abundance indicate that the upper limit of water present is far too low to produce so large an effect (Jastrow and Rasool, 1962).

If Dollfus' result is correct then the problem should be re-examined. Kaplan (1963) believes the necessary atmospheric absorption to complement the CO_2 absorption is provided by organic molecules. We have already noted that this seems unlikely. A possibility that merits investigation is clouds consisting of dust, and in particular inorganic carbonates. These solids are in general colorless and have relatively strong absorption bands in the 3-4 μ region where the Venusian CO_2 is relatively transparent, and which contains a large part of the thermal radiation emitted by the surface.

Barrett (1961) has considered whether CO_2 and possibly water could explain the microwave spectrum. The gently sloping curve in Fig. 22 is the result of Barrett's calculation for an atmosphere containing 25 per cent CO_2 and 75 per cent N_2, a surface pressure of 20 atmospheres, and a surface temperature of 600°K. More recent estimates of the CO_2 abundance (Kaplan, 1962) indicate that it is likely to be less than 25 per cent. Further, the characteristic non-resonant CO_2 absorption, which is aresult of the high pressure, does not appear to fit the apparent steep gradient in the observed spectrum. The other curve shown in Fig. 20 for comparison was constructed by assuming a model in which an atmosphere at 350°K with optical depth proportional to λ^{-4} overlay a surface at 600°. Such a wavelength dependence is much too rapid to be explained by absorption in atmospheric dust particles due to lattice modes occurring in the far infrared. The decrease in temperature at 40 cm is attributed by Drake to a dependence on wavelength of the surface emissivity. At the longer wavelengths the surface appears smoother and there is consequently less emission, particularly near the limbs.

It is clear that a careful measurement of the brightness of Venus over a range of wavelengths in the neighborhood of 1 cm will be helpful in determining what atmospheric constituent is responsible for the absorption at shorter wavelengths. A search in the visible and infrared bands for any constituent that has absorption features near 1 cm should also be conducted. More observations at wavelengths longer than 10 cm to confirm Drake's hypothesis concerning the surface emissivity will also be useful. Finally, the observations with the two element interferometer made by Clark (1963) show the importance of this type of measurement. Such efforts should certainly be pursued, if possible with longer baselines to improve resolution.

Radar Experiments

The first radar contact with Venus was reported by the Lincoln Laboratory of the Massachusetts Institute of Technology at the time of the 1958 inferior conjunction (Price, et al, 1959) at 68 cm. The signals were weak and considerable data reduction was necessary to retrieve the signals from the noise. A value of 149,470,544 km for the astronomical unit was inferred from the range data. During the following conjunction, the same experimenters, using somewhat better apparatus, were unable to repeat the experiment. However, a group operating at the Jodrell Bank experimental station at a wavelength of 73 cm were able to perform the experiment and obtained a value for the astronomical unit of 149,468,855 km which agreed with that found by the MIT group (Evans and Taylor, 1959). On the other hand, their echoes were about 18 db weaker than those previously reported. After data reduction, their signal was 2 1/2 times the residual noise.

Then during the inferior conjunction of April, 1961, both these groups and, in addition, the Jet Propulsion Laboratory of the California Institute of Technology repeated the experiment, and all three obtained a new value for the astronomical unit in close agreement with one another. Thompson et al (1961) at Jodrell Bank found it to be 149,599,755 km and the signals to be much stronger than from the moon at 73 cm. The MIT observers (Millstone Staff, 1961) at 68 cm obtained a value of 149,597,700 km for the astronomical unit (within 1500 km). They also found the reflection coefficient of Venus to be about 12 per cent of that of a perfectly reflecting sphere and the doppler broadening due to rotation of the planet to be less than 1 cps. From this they suggested that the apparent period of rotation might be equal to the synodic period of 584 days. Operating at a wavelength of 12.6 cm with a more sensitive system, the experimenters at the Jet Propulsion Laboratory obtained a value of 149,599,000 $\pm$ 1500 km for the astronomical unit, a reflectivity of 10-15 per cent, and from a comparison of their doppler broadening data with similar data for the moon a period of rotation of 225 days forward (Victor et al, 1961). It was clear that most of the echo was coming from the nose of the planet as in the case of the moon. Furthermore, transmitting circular polarization and receiving on either the same or opposite sense of polarization, they found 12 db more signal returned in the latter case. Comparing these data with similar lunar data, they concluded that the roughness of Venus is similar to that of the moon,but that the dielectric constant is somewhat higher, about 3.6.

During the November, 1962 conjunction the Jet Propulsion Laboratory (Goldstein et al, 1963) repeated their previous experiment with improved sensitivity, obtaining echoes about 23 db above the noise. From the day to day motion of a feature on the spectrum of the echoes and also from a range-doppler analysis of the echoes, they obtained a sidereal period of about 250 days retrograde for the planet. They again obtained a reflection coefficient of about 12 per cent.

At this time echoes were also obtained at 6 m by the Ionospheric Experimental Station in Peru (J. Ochs, 1963). Fading of the signals from echo to echo was observed. Perhaps the most interesting results reported were obtained by the MIT solar radar facility at El Campo, Texas (Chisolm, 1963). Operating at a frequency of 7.9 m, they observed echoes which were twice as large as those obtained at 68 cm at Millstone (1961). These echoes are also significantly larger than those obtained by any other of the observers referred to above, and could perhaps be attributed to an ionosphere on Venus.

More sensitive radar equipment will in the future undoubtedly pin down the rotation rate and reveal surface features as in the case of the moon. Such data will contribute to the knowledge of the invisible surface. Certainly the long wavelength observations should be pursued to probe the Venus ionosphere, if it exists.

VI. Mars

Several broad surveys of our knowledge of Mars have been published in the last few years. The most extensive is the exhaustive analysis of de Vaucouleurs (1954). Later, more restricted reviews were written by Hess (1961) and Öpik (1962). A 1960 conference on planetary atmospheres produced a report summarizing the state of knowledge of the atmospheres of Venus and Mars (Kellogg et al, 1961). Specific topics have been examined by Dollfus (1961) -- polarization; Dollfus (1961) -- visual and photographic studies; Sinton (1961) -- infrared radiometry; and Harris (1961) -- colorimetry of the entire disk.

Visible Region

Photometric studies have been reported by several authors and show an increase in reflectivity towards the red which seems to be present for the dark areas as well as the light areas. The spectral dependence of the geometric albedo for the entire planet, Table 1, reveals the net effect. To draw conclusions about the surface, the effect of the atmosphere must be factored out. The gross uncertainties and assumptions in this procedure have been discussed in detail by de Vaucouleurs in his monograph (1954). In the years since the publication of this book there appear to be no developments which have improved the dependability of the deductions. Öpik (1962a) has reanalyzed earlier data with the assumption that the scattering diagram for the Martian surface is the same as for the Moon; however, his statement that the uniform brightness of the full Moon "...is a well known general property of rough surfaces" is incorrect. Rather, it is a very particular property of surfaces with a peculiar type of roughness and is certainly not general. By analogy with terrestrial experience the existence of loose dust on Mars would be expected to give a photometric function more nearly like Lambert's Law.

From the reflectivity in the visible and near infrared, uncorrected for atmospheric effects, Kuiper (1952) has tentatively assumed that the bright areas consist "...of igneous rock, similar to felsitic rhyolite." Visual polarization measurements, however, have led Dollfus (1961) to the conclusion that the bright covering is finely powered limonite, $Fe_2O_3 \cdot 3H_2O$. The lack of agreement in these two conclusions demonstrates the limitations of visible observations for obtaining compositions.

On the basis of various arguments, one of the strongest being Kuiper's (1952) observation of a decreased near infrared reflectivity, it has been argued that the polar caps consist of a thin layer of hoar frost. This conclusion now seems definite in view of the recent positive identification of H_2O in the Martian atmosphere (Spinrad et al, 1963; Dollfus, 1963).

Of the atmospheric phenomena it is generally accepted that the yellow clouds consist of small dust particles and the bright white clouds of ice particles. But the nature of the blue or violet layer still seems controversial. The decrease in the albedo in the blue, together with a general disappearance of surface contrast and appearance of a nearly uniformly bright disk, at least in the works cited by de Vaucouleurs (1954), has been attributed to two different mechanisms. The first supposes the presence in the Martian atmosphere of small particles, of the order of 0.3 - 0.4 μ diameter, of ice or of solid carbon dioxide. Calculations of brightness across the disk have been carried out assuming conservative isotropic scattering and a surface reflection approximating Lambert's Law. The results are in fairly good agreement with the observations and lend support to this approach incorporating a non-absorbing, reflecting haze over a weakly reflecting surface for which the back-scattered reflection decreases with increasing angle of incidence. As in most calculations on planetary cloud phenomena the results must be regarded as only tentative (de Vaucouleurs, 1954).

This approach has been challenged by Öpik (1962a). He adopts data of Barabashev and Chekirda showing limb darkening and concludes that the violet haze cannot be merely scattering but must also be absorbing. This belief is based on the assumption that the surface of Mars is similar to the Moon in having a constant back-scattering reflection independent of the angle of illumination. Since the haze whose properties he calculates is absorbing, particles of ice or solid carbon dioxide by themselves are ruled out. The absorption may be provided by an atmospheric constituent or, more probably, by the particles themselves. This introduces the possibility of fine dust, carbon smoke, or some other absorbing substance.

Since 1950 Dollfus (1957a, 1957b) has employed new fringe and double-image photometers to examine the brightness of the light and dark areas as functions of the phase angle and distances from the central meridian. Pronounced limb darkening was observed for all visible wavelengths. The data in orange light were analyzed to obtain the relative brightness of the atmosphere. This was found to be 43 per cent higher than that derived from his polarization measurements. The discrepancy was ascribed to a suspension of dust particles with diameters slightly greater than 0.6 μ, having a greater influence on the brightness than on the polarization. The analysis also gave the surface brightness at 60^{o} from the central meridian as 0.30 times that at 0^{o}, a value intermediate between a Lambert surface (0.5) and the lunar surface (0.0).

The choice between these two interpretations depends on the photometric data adopted and on what the photometric function of the surface is. Our earlier remarks suggest that Öpik's lunar analogy is incorrect; accordingly, non-absorbing particles are favored although the possibility of absorbing particles should not be excluded.

Infrared Region

Some of the most provocative Martian observations have been in the infrared by Sinton (1957; 1959; 1961a). He has used the 200-inch Mt. Palomar reflector with a grating spectrometer to record 3-4 μ spectra of different areas of the Martian disk. His spectra, Fig. 22, possess features which are more pronounced for the dark areas than for the light areas. He interprets them as absorption bands at 2710, 2793 and 2900 cm^{-1} (Mars I, II and III bands respectively), and believes they are due to organic material including carbohydrates. Colthup (1961) has assigned the Mars I band to acetaldehyde on the basis of its low wavenumber and high relative intensity. This view has been criticized by Rea (1963) who notes that acetaldehyde is very volatile and would be expected to be in the gas phase, thus producing bands of similar intensity over the light and dark areas. The assignment of the features to surface organic matter remains possible and is clearly of great significance with respect to a possible Martian biology.

This assignment has been recently studied in some detail by Rea et al (1963a) who have recorded the 2.5 - 4 μ reflection spectra of a large number of samples, both organic and inorganic. Their conclusions may be summarized as:

(1) It is not clear whether the observed curve consists of absorption minima or S-type reflection features, so that the corresponding resonant frequency may fall within a considerable range;

(2) Carbohydrates cannot explain the Mars I band because its relative intensity is much too high;

(3) Both the Mars I and II bands, if due to organic matter, must be assigned to the CH's of aldehyde groups present in high relative concentrations; no spectra were recorded which were appropriate;

(4) Inorganic carbonates could explain the III band but probably not the I and II bands; and

(5) The increase in apparent Martian reflectivity towards lower wavenumbers may be due to the superposition of surface emission on the reflection, Fig. 23, or to the wing of an intense absorption band produced by H_2O present in the surface as liquid (within plants), water of crystallization, or as an adsorbed phase.

The presence of features in the 3-4 μ spectrum of Mars has been confirmed by Moroz (1963). His spectra, for which there was no resolution on the disk, had minima at 3.43 μ (2915 cm^{-1}), 3.53 μ (2830 cm^{-1}), 3.59 μ (2785 cm^{-1}) and 3.68 μ (2710 cm^{-1}). It is difficult to accept the splitting of Sinton's Mars II band into two since his features are separated by only 0.06 μ, whereas the spectral resolution was only 0.09 μ.

The interpretation of the 3-4 μ Mars spectrum is considered to be still an open question. To answer this important question more data are required, particularly Martian spectra with both better spectral and spatial resolution.

The 8-13 μ infrared spectrum of the entire Martian disk has been obtained by Sinton et al (1960a), Fig. 24. The authors used this spectrum to conclude that "...less than 20 per cent of the surface material of Mars is silicates." This was based on the fact that quartz has a reststrahl with a peak reflection coefficient of 0.85, and hence an emissivity of 0.15, at 8.8 μ.

However, this conclusion regarding the scarcity of silicates on the surface appears on a closer examination to be rather weak. First, silicates have reflection maxima in the approximate broad range 8.8 - 11 μ, so that a range of mineralogical types present would result in a decreased emissivity over a considerable spectral region. But the most important criticism is that surface roughness will play a significant role in the emission properties and must be considered. A dusty silicate surface will have a higher emissivity than a polished surface. Data on the actual effect are relatively few. Bell et al (1957) have measured the emission of a sandy beach and observed an emissivity minimum of only ca. 16 per cent at 9 μ. This is not completely applicable to the Martian observations since the observed radiation from the terrestrial surface includes sky radiation reflected from the sand. Normal reflectivity measurements were also made by Bell et al on samples of Lake Erie sand. Assuming the surface obeys Lambert's Law the albedo at 9 μ is 0.26. This should be regarded as an upper limit so that the minimum normal emissivity will be 0.74. Without considering additional factors such as smaller particles or a fluffy surface it is clear that the surface may well have a high concentration of silicates on the surface.

This discussion, together with other results of Bell et al, lead us to the conclusion that the surface emissivity is probably higher than 0.9 in the 8-13 μ region, an important consideration in evaluating the radiometric measurements. Radiometer studies of Mars have been treated by Pettit (1961) and Sinton (1961). The measurements by Lampland at Lowell Observatory using the total radiation in the 8-13 μ window have been analyzed and discussed by Gifford (1956) who has presented the data in the form of isotherms for the different seasons. The temperatures at local noon range from a maximum of 300°K to a minimum less than 220°K.

The more recent radiometric work of Sinton and Strong (1960a) is in good agreement with Gifford's results. From the observed temperature diurnal variation they deduced a thermal inertia between 0.004 and 0.01. The authors point out that the effect of the Martian atmosphere was not included in their calculations. Its influence is to decrease the temperature variation and accordingly increase the apparent thermal inertia. Taken in conjunction with the remarks made on the corresponding lunar analyses this suggests that the thermal inertia may be somewhat lower, favoring a low density surface material.

The observed temperatures will have to be corrected for an emissivity less than 1 and for absorption by colder CO_2 in the atmosphere. Nevertheless, it is expected the corrections will be small, the actual temperatures being less than 5°C higher than those observed.

As for the various proposals concerning the surface composition of Mars there appear to be no definite answers at the present time. Arguments, both pro and con, can be introduced when discussing materials such as limonite, felsitic rhyolite, and vegetation, but none is definitive. Recent writers on the subject seem to favor a Martian biology as the source of the dark areas. The arguments for this point of view have been examined by Rea (1963) and their tenuous character noted. An alternative worthy of more serious consideration is a blend of the volcanism ideas of McLaughlin (1954) and Kuiper (1957a).

Microwave Experiments

Radio emission from Mars has been reported on two occasions by workers at the Naval Research Laboratory. Near the favorable opposition of 1956 Mayer et al (1958b) obtained an effective disk temperature of $218 \pm 50^{\circ}$ using a conventional receiver operating at a wavelength of 3.15 cm. Shortly after the opposition of 1958 Giordmaine et al (1959), using a maser preamplifier at 3.14 cm, obtained a disk temperature of $211 \pm 20^{\circ}$. In contrast, the average disk temperature observed in the infrared by Menzel et al (1926) lay in the range of 237-254°. Mayer (1961) suggests that the difference is significant and attributes the lower microwave temperature to the fact that it may arise in a layer which is farther below the level in the Martian surface from which the infrared radiation emanates. If the thermal inertia of the Martian soil is sufficiently great compared with the planet's period of rotation, the 3 cm radiation will correspond to the average planetary temperature. This situation is familiar from the wavelength dependence of the lunar phase effect. For a Bond albedo of .148 the radiation temperature for Mars is 217° (Kuiper, 1952) which agrees well with the 3 cm value of 211°.

Recently Drake (1963) has obtained a temperature of $177^{\circ} \pm 17^{\circ}$ for Mars at 10 cm. This is even lower than the 3 cm results, and Drake attributes the lower temperatures to the effect of surface emissivity changing with wavelength. At the longer wavelengths the surface is effectively smoother so that the emission from regions near the limbs is less and the integrated temperature is therefore lower. This is reasonable in view of the visible observations that dust must cover large areas of Mars. It is also of interest that this effect was not detected in the 10 cm work on Venus, since its surface is perhaps dustier than Mars'.

VII. The Major Planets

Photometric and polarization observations are discussed by van de Hulst (1952), Kuiper (1952), Harris (1961), Dollfus (1961) and Öpik (1962b). It is repeatedly stressed that the deductions from the observations are extremely tentative due to the several factors operating simultaneously in the atmospheres and to the inability to observe these planets over a broad range of phase angles. Auxiliary assumptions based on other considerations must be introduced as Öpik has done in his monographic report on Jupiter (1962b). Rather than become involved in this we will restrict ourselves to reporting the geometric and Bond albedos, Table 1 (Harris, 1961), and the radiometric data.

Jupiter

A radiometric temperature of 120°K was obtained by Menzel et al (1926) from measurements in the 8-13 μ window. This was supported by Murray and Wildey (1963) who found T = 128°K with a standard deviation of 2.3°K. The presence of significant amounts of NH_3 with its strong absorption band near 10.5 μ in the Jovian upper atmosphere means that this temperature refers to some effective level in the atmosphere and not to the clouds (Kuiper, 1952).

Jupiter has been found to be a strong source of radio emission both at centimeter and decimeter wavelengths. In the centimeter range the equivalent disk temperature rises from about 150° at 3 cm to 50,000° at 68 cm. Then at decimeter wavelengths the signals are stronger, somewhat irregular, and very unlike thermal noise. Most of the radiation at wavelengths longer than about 10 cm is likely due in some manner to emission from an ionized layer surrounding the planet. As we are here confining our attention to emission from planetary clouds and surfaces, we shall refer the reader to the excellent reviews of Mayer (1961), Burke (1961), Gallet (1961) and Roberts (1963) for a discussion of the longer wavelength Jovian emission.

Observations of emission from Jupiter were made by Mayer et al (1958b) at 3.15 cm in 1956 and 1957, and by Giordmaine et al (1959) at 3.03 cm and 3.17 cm in 1958 and 1959. The former obtained a disk temperature of 145 ± 18° and the latter a temperature of 172 ± 20°. With the exception of the use of a maser preamplifier in the latter measurements, the equipment used and calibration procedures observed were the same in all these observations, so that the difference may be significant. Calculations made by Giordmaine and Alsop (1961) based on a model atmosphere similar to one proposed by Kuiper (1952, model b) show that all of the 3 cm radiation is likely to be thermal emission from the atmosphere arising from the ammonia that is known to be present from spectroscopic observations. Ammonia possesses a strong absorption band centered at 1.28 cm due to hindered vibrations. None of the other important atmospheric constituents: He, H_2, CH_4, have significant absorption. Similar calculations by Field (1959) have shown that the thermal emission from the ammonia is insufficient to account for the longer wavelength radiation.

Radiation from Jupiter was observed by Kuz'min and Salomonovich (1961) at 8.0 mm, although no attempt was made to estimate its absolute magnitude. Rather, they assumed the disk temperature to be 140° and used this value to calibrate their antenna for their observations of Venus. Recently, one of the authors and D. Thornton (Thornton and Welch, 1963) measured the emission at 8.35 mm and obtained an equivalent disk temperature of $144 \pm 23°$. Calculations show this to be in accordance with emission from a thin layer of ammonia near the visible cloud tops in agreement with Kuiper's model atmosphere (1952).

Further accurate measurements spanning the range of 0.6 to 3.0 cm. (preferably on one instrument) will provide valuable information about the total atmospheric density near the visible cloud tops. A sweep across the ammonia inversion band centered at 1.28 cm may reveal some structure in the emission temperature which can be related to the total pressure and density at the cloud tops. The total amount of the major constituents, He and H_2, that is present is not well known because of the difficulty in observing them spectroscopically.

Saturn

An unexpected result was obtained by Kuiper (1952) in his near infrared observations of Saturn's rings. He observed a sharp decrease in their reflectivity near 1.5 μ. This is similar to the spectrum of the Martian polar caps and led Kuiper to conclude "...that the rings are covered by frost, if not composed of ice."

The 8-13 μ temperature obtained for Saturn by Menzel et al (1926) was 128°K. However, Murray and Wildey (1963) report that they were unable to detect any 8-13 μ signal and set an upper limit for the temperature of

$105^{o}K$. The discrepancy between these two values is significant enough to justify further radiometer work on Saturn using telescopes larger than the 19" one used by Murray and Wildey.

The first report of radio emission from Saturn is that of Drake and Ewen (1958) at a wavelength of 3.75 cm. They concluded only that the very weak signal they received was consistent with emission from the optical disk alone at the then accepted infrared temperature of 125^{o}. Cook et al (1960) observing at 3.45 cm with a maser preamplifier obtained an equivalent disk temperature of 106 ± 21^{o}, closer to the most recent infrared value. A disk temperature of 196 ± 44^{o} at 10 cm has recently been reported by Drake. The most probable explanation for this high value is the suggestion by Drake that this emission comes from deeper, warmer layers. Clearly, more observations are needed, particularly at the longer wavelengths to confirm and perhaps explain the higher temperature obtained by Drake.

Acknowledgment

It is a pleasure to express our appreciation to R. Strom and D. Thornton for many valuable discussions, and to S. Silver for a critical reading of the manuscript.

FIGURE CAPTIONS

Figure

1 The refractive index, n, extinction coefficient, k, and reflection coefficient, R, for an isolated medium intensity infrared band. The reflection coefficient is calculated for normal incidence. (After Rea et al, 1963).

2 The transmission and reflection curves of the C=O stretching band of lucite. The transmission curve is for a 25 μ thick film, the reflection curve for a 1 cm thick block. (After Rea et al, 1963).

3 The absorption and reflection coefficients for the LiF Reststrahl near 400 cm^{-1}. (After Gottlieb, 1960).

4 The scattering diagrams calculated by Mie theory: The ordinates are log intensities and the abscissae phase angles. The refractive index is denoted by m and the quantity $2\pi r/\lambda$ by x. (After van de Hulst, 1957).

5 The scattering diagram for water drops with $2\pi r/\lambda = 30$ calculated using geometrical optics; the lower solid curve includes reflection and refraction, the upper solid curve these effects plus diffraction. The dashed line is through points calculated using several terms in the exact Mie expansion. The ordinate is the intensity and the abscissa is the phase angle. (After Bricard, 1943).

6 The brightness dependence of several lunar areas on the phase angle. The ordinate is aR and the abscissa the phase angle. (After Sytinskaya and Sharonov, 1952).

7 Indicatrices of reflection for the lunar maria (dashed lines) and terrae (solid lines). These are polar plots of the radiation scattered at various angles for fixed angles of incidence. The points chosen were on the lunar equator. The angle of incidence is denoted by i. (After Orlova, 1956).

8 Polarization of the integrated light from Moon (A), Mercury (B) and Mars (C). The dotted lines D and E apply to the strongest and weakest polarizing areas in the Moon. The ordinate is the polarization in units of 0.001, the abscissa is the phase angle. (After Dollfus, 1961).

9 Reflecting properties of AgCl "fairy castles," 9a, and the lichen <u>Cladonia rangeferina</u>, 9b. The long dash lines are lunar curves, the short dash lines the curves for a Lambert surface. The reflected intensities were measured at a constant angle of reflection, ϵ , for different angles of incidence, i. (After Hapke and van Horn, 1963).

10 An example of a lunar radar echo obtained by Hey and Hughes (1959) at 10-cm wavelength. The ordinate is approximately in units of intensity.

Figure

11 An average of many lunar echoes at 68 cm. The abscissa is cos θ, the angle of incidence on the surface, obtained by a transformation from the distribution of echo in time. The curve labeled Lommel-Seeliger Law is proportional to cos θ ; the curve labeled Lambert Law is proportion to $\cos^2 \theta$. (After Pettengill, 1960).

12 The average echo power at 3.6 cm and 68 cm obtained by Evans and Pettengill (1963) along with the observations of Hughes (1961) at 10 cm. The curves have been normalized at the origin to emphasize the wavelength dependence. (After Evans and Pettengill, 1963).

13 A schematic representation of the spatial resolution on the moon obtainable by dividing the returns up both with respect to range and doppler shift. For one choice of range interval and doppler frequency interval, echoes from only the two dark patches P and P' will be present. (After Pettengill and Henry, 1962).

14 The variation of infrared temperature of a point near the center of the lunar disk throughout a lunation. The solid line was calculated assuming a thermal inertia of 0.0023. (After Sinton, 1962).

15 Temperature measured during the course of three eclipses: a - June 14, 1927, by Pettit and Nicholson; b - October 27, 1939, by Pettit; c - July 26, 1953, by Sinton and Strong. In c the large dots refer to a point 2' from the east limb, and the small dots to a point 9' from the east limb limb. The solid curves in b and c were calculated using the thermal inertias indicated. (After Sinton, 1962b).

16 Radio brightness temperature contours on the lunar disk at 8 mm for various phases ($\phi = 180^\circ$ corresponds to full moon). These were taken with the 22-meter antenna of the Lebedev Physics Institute. (After Salomonovich, 1962).

17 The observed equivalent disk temperatures of Mercury (Howard, et al, 1962) at various phases. The solid curve is the infrared temperature (Pettit, 1961). The dashed curve was constructed by Howard et al (1962) to fit their data assuming no radiation from the non-illuminated side and a temperature variation of $\cos^{1/4} \theta$ on the bright side. (After Roberts, 1963).

18 The polarization of integrated light from Venus as observed by Lyot. The ordinate is the polarization in units of 0.001, the abscissa is the phase angle. (After Dollfus, 1961).

19 (a) Near infrared spectra of Venus, solid line, and the sun, dashed line. The numbers on the solid line refer to CO_2 bands in the Venus atmosphere.
(b) Near infrared reflectivities of layers of ice crystals. The intense, broad minimum near 2.0 μ is missing from the Venus spectrum. (After Kuiper, 1962).

Figure

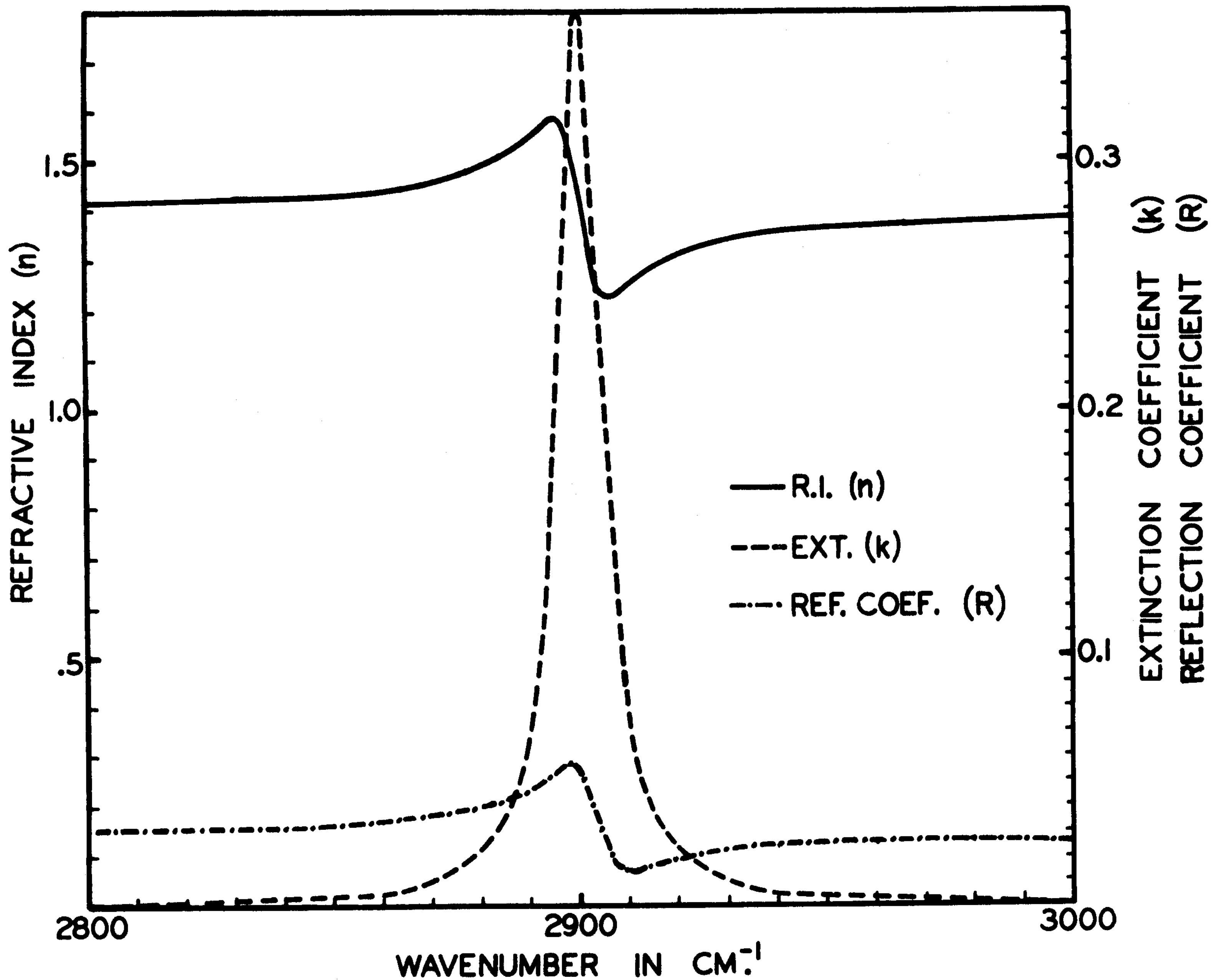
20 The equivalent disk temperature of Venus near inferior conjunction. The experimenters are detailed in the text. Most of these data are from the November, 1962 conjunction. The gradually sloping solid line is taken from Barrett (1962) for an atmosphere consisting of 25 per cent CO_2 and 75 per cent N_2, a surface pressure and a temperature of 20 atmospheres and 600°K. The other curve is a best fit to the data for an atmosphere at 350° and optical depth proportional to λ^{-4} overlying a surface at 600°.

21 The phase variation of the disk temperature of Venus. (a) The NRL 3-cm and 10-cm data assembled by Mayer (1961) and the first phase data of Kuz'min and Salomonovich (1960). (b) The 1961 10-cm data of Drake (1961) near conjunction and a value also obtained by Drake (1962) near superior conjunction. (After Roberts, 1963).

22 Infrared spectra of Mars in the 3-4 μ region. Sinton divided the observed curves by a recorded solar spectrum to find the "reflectivity" curves in the figure. The inserts indicate the shape and location on the disk of the aperture. The ordinate is in arbitrary units. (After Sinton, 1959, 1961a).

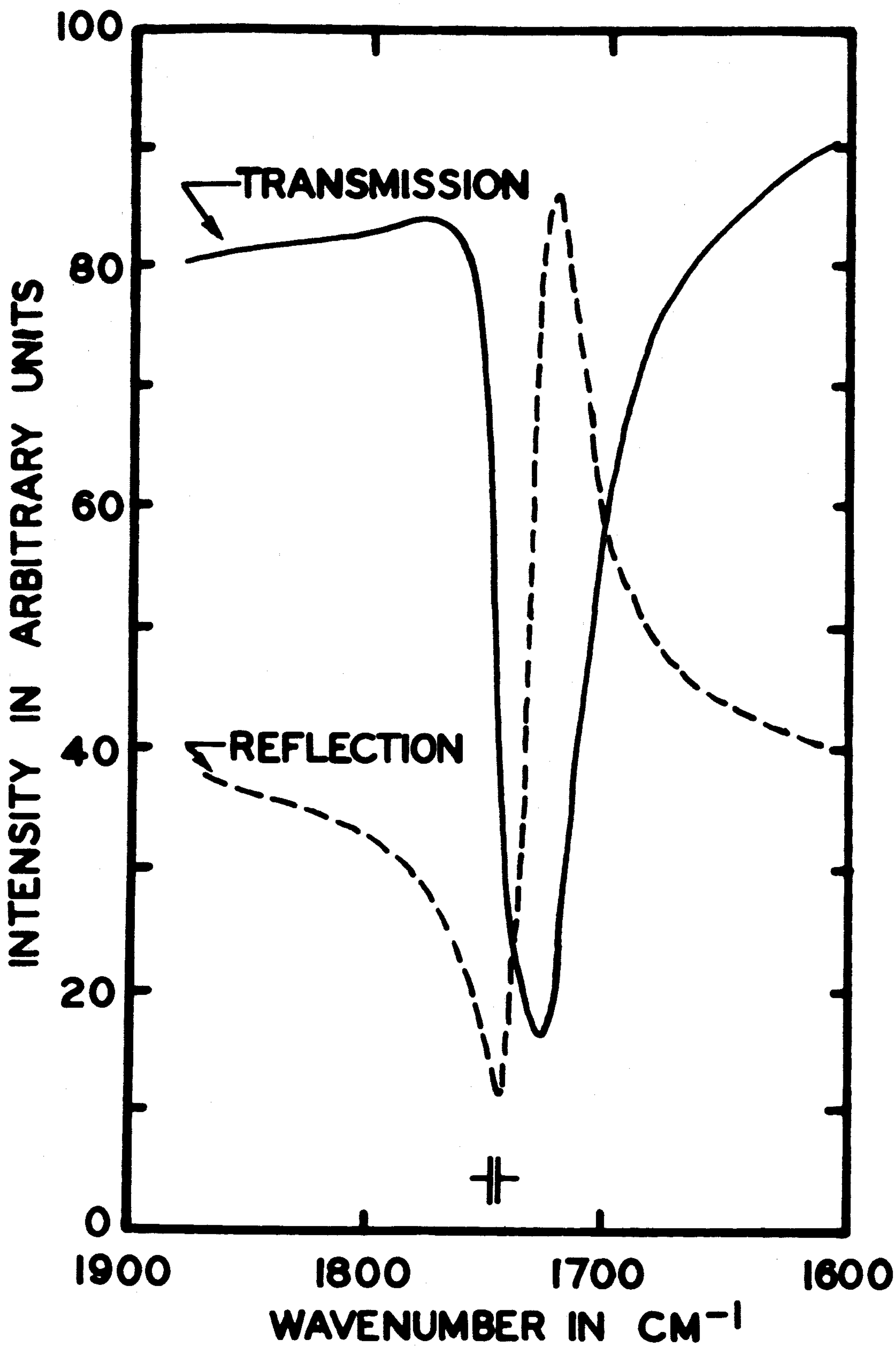
23 Calculated values for the reflected solar radiation (assuming a 5500°K sun) and emitted thermal radiation for a Martian area perpendicular to the solar rays. (After Rea et al, 1963a).

24 The spectrum of Mars in the 8-13 μ region after a correction for telluric absorption. (After Sinton and Strong, 1960a).



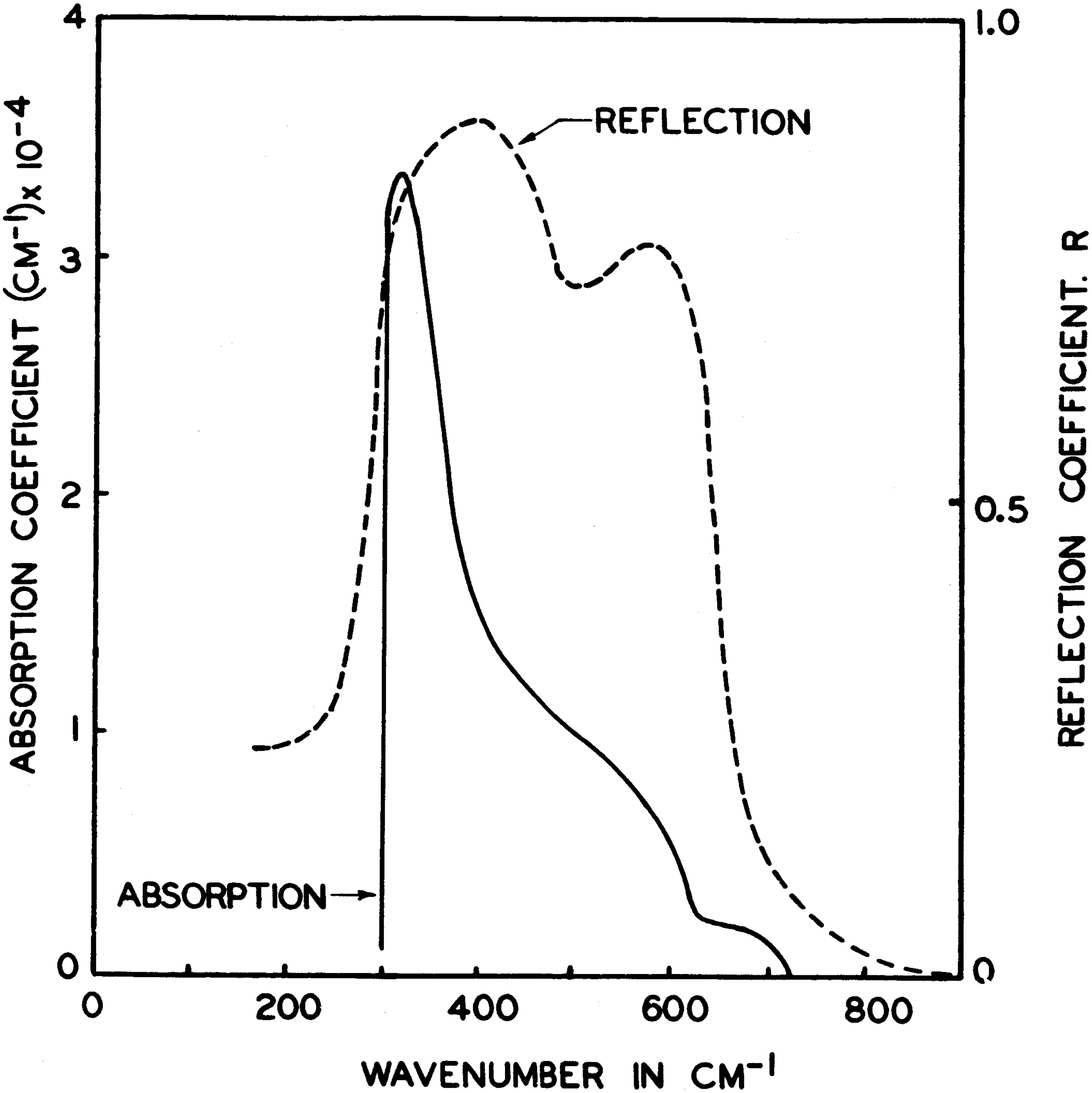
1.5
1.0
.5
REFRACTIVE INDEX (n)
0.3
0.2
0.1
EXTINCTION COEFFICIENT (k)
REFLECTION COEFFICIENT (R)
R.I. (n)
EXT. (k)
REF. COEF. (R)
2800
2900
3000
WAVENUMBER IN CM.$^{-1}$

Figure 1



100
80
60
40
20
0
INTENSITY IN ARBITRARY UNITS
TRANSMISSION
REFLECTION
1900
1800
1700
1600
WAVENUMBER IN CM^{-1}

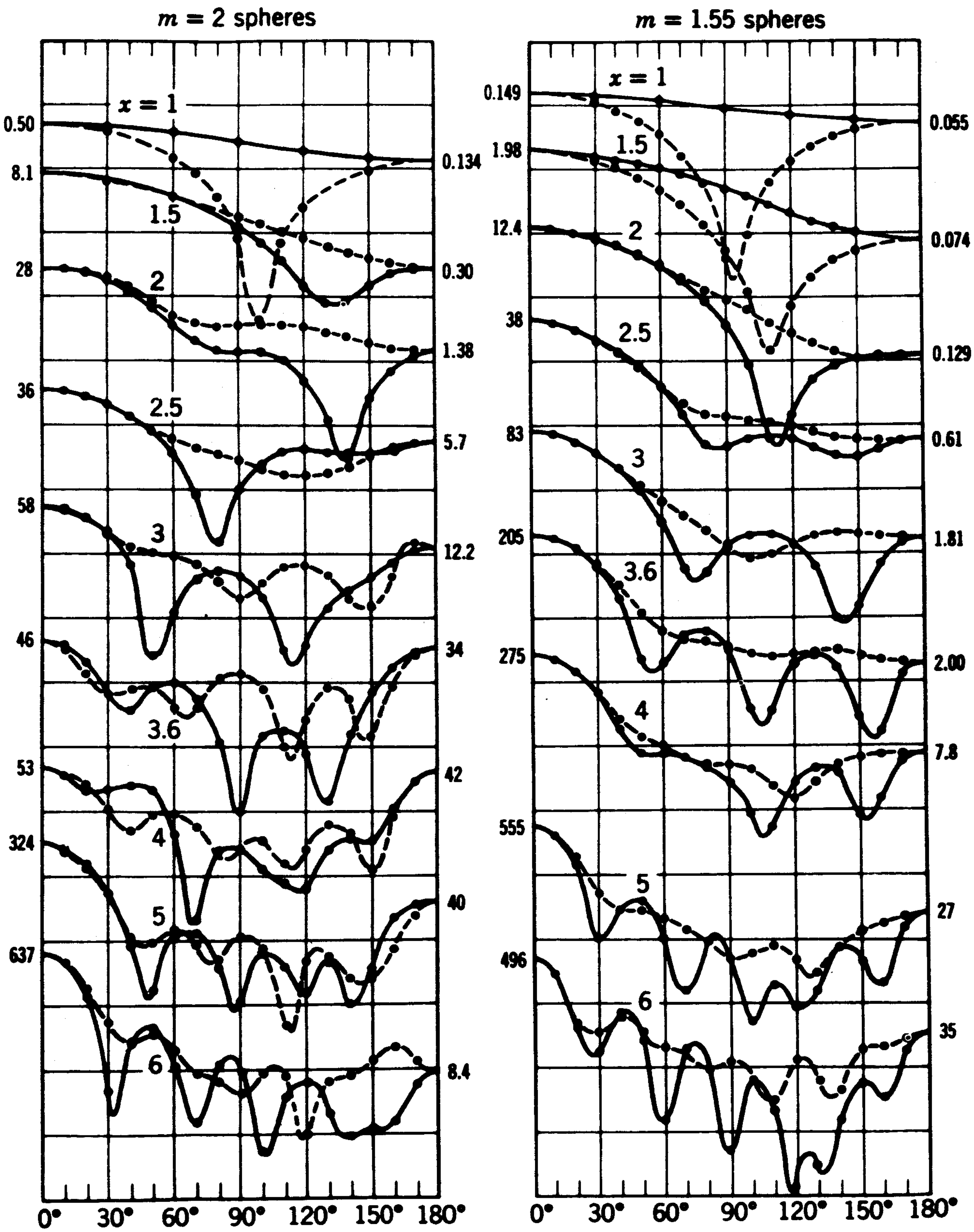
Figure 2



ABSORPTION COEFFICIENT (CM^{-1}) x 10^{-4}
REFLECTION COEFFICIENT. R
REFLECTION
ABSORPTION
0
1
2
3
4
0.5
1.0
0
200
400
600
800
WAVENUMBER IN CM^{-1}

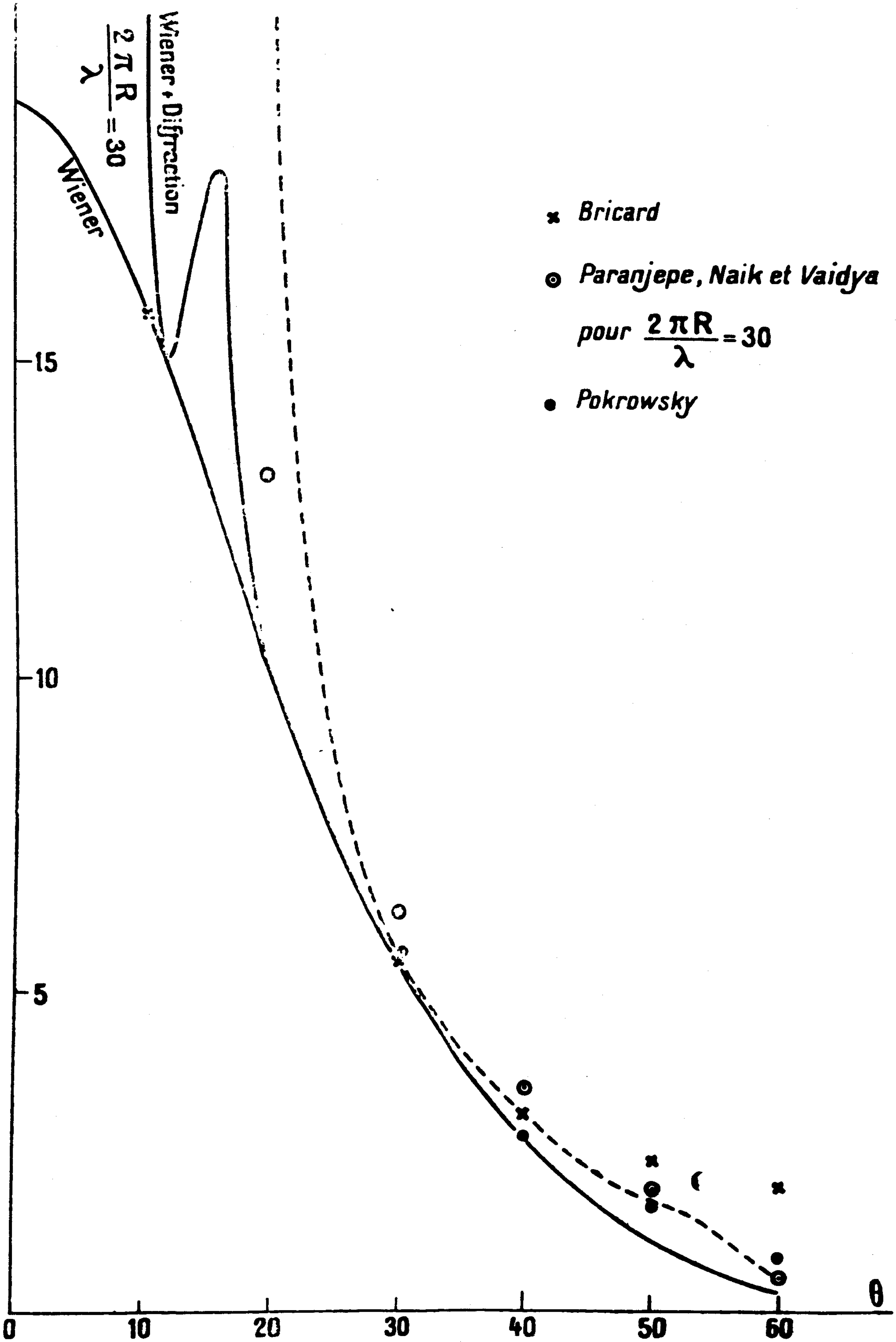
LiF

Figure 3



m = 2 spheres
m = 1.55 spheres
x = 1
1.5
2
2.5
3
3.6
4
5
6
0.50
8.1
28
36
58
46
53
324
637
0.134
0.30
1.38
5.7
12.2
34
42
40
8.4
0.149
1.98
12.4
38
83
205
275
555
496
0.055
0.074
0.129
0.61
1.81
2.00
7.8
27
35
0°
30°
60°
90°
120°
150°
180°

Figure 4



Wiener
Wiener + Diffraction
$\frac{2\pi R}{\lambda} = 30$
Bricard
Paranjepe, Naik et Vaidya pour $\frac{2\pi R}{\lambda} = 30$
Pokrowsky
15
10
5
0
10
20
30
40
50
60
θ

Figure 5

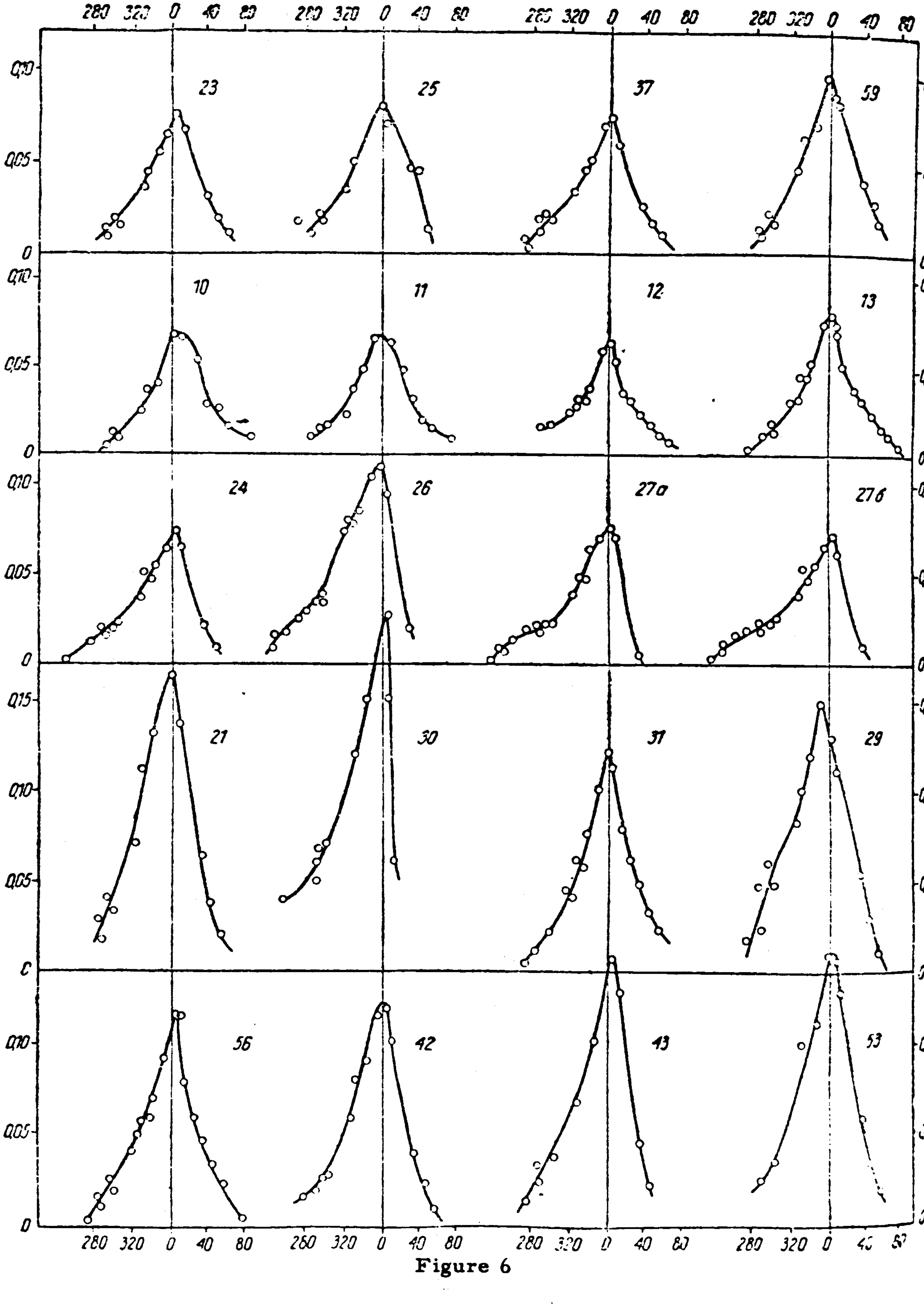

23
25
37
59
10
11
12
13
24
26
27a
27б
21
30
31
29
56
42
43
53
280 320 0 40 80
0,10
0,05
0,15
0

Figure 6

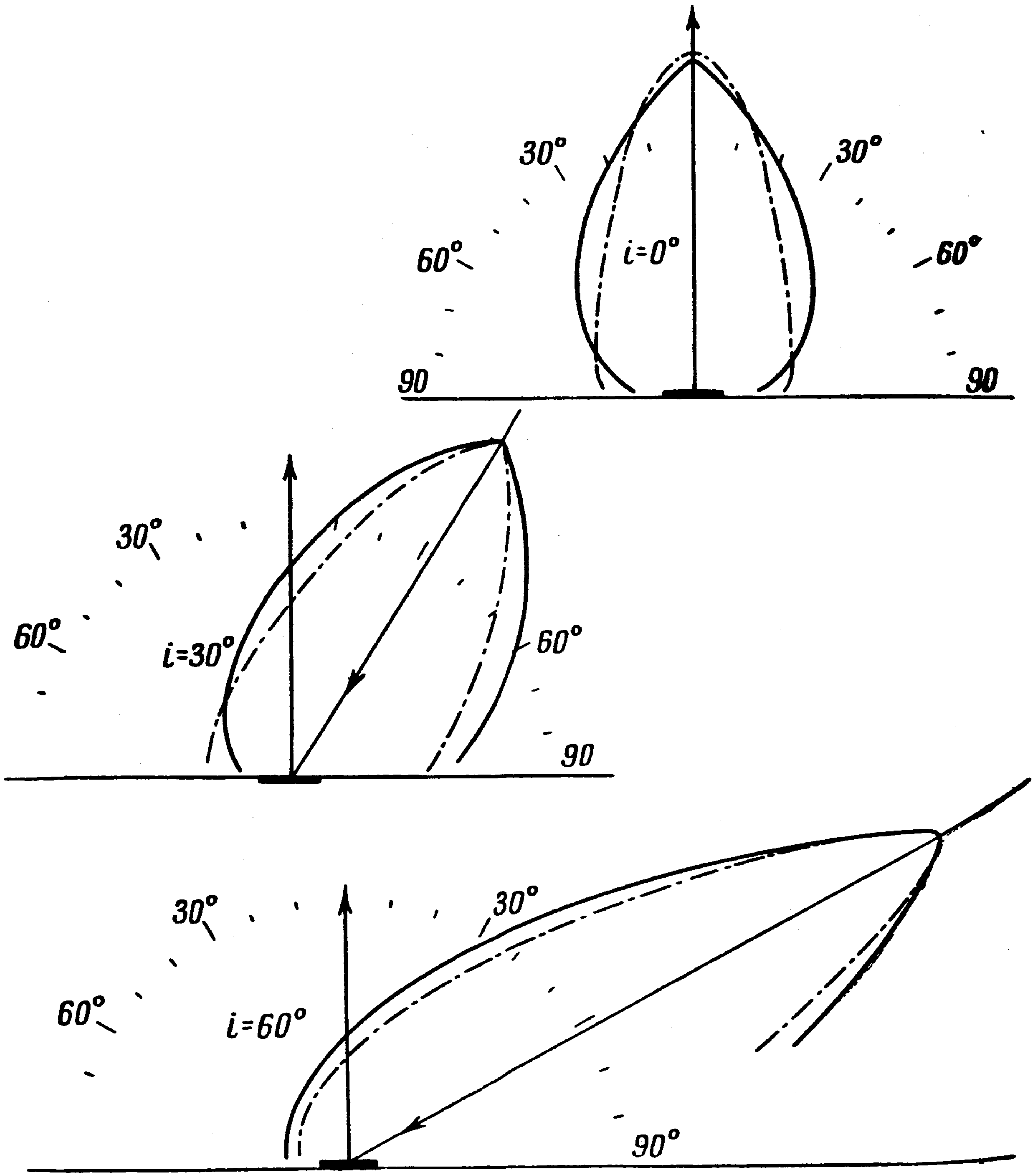
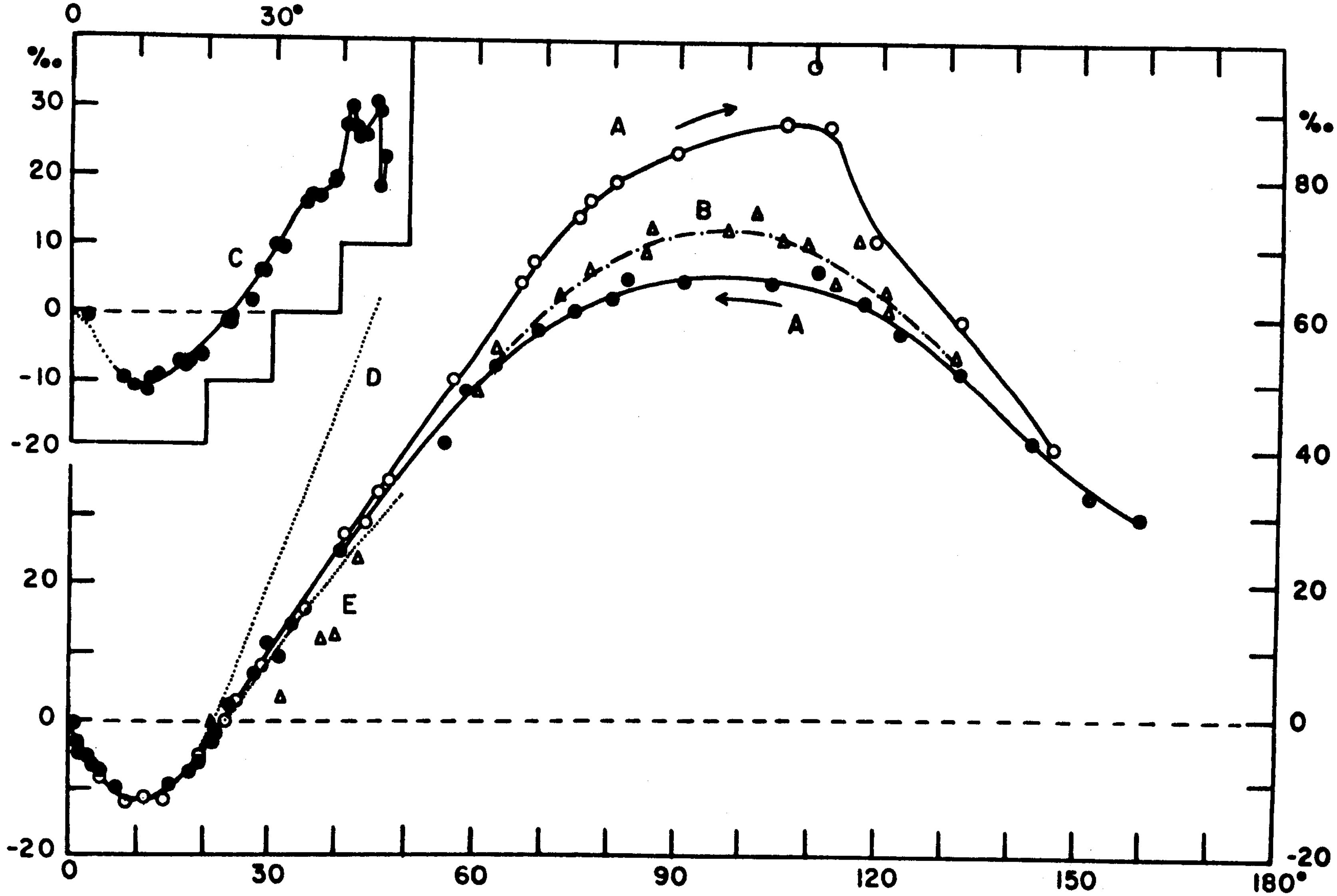


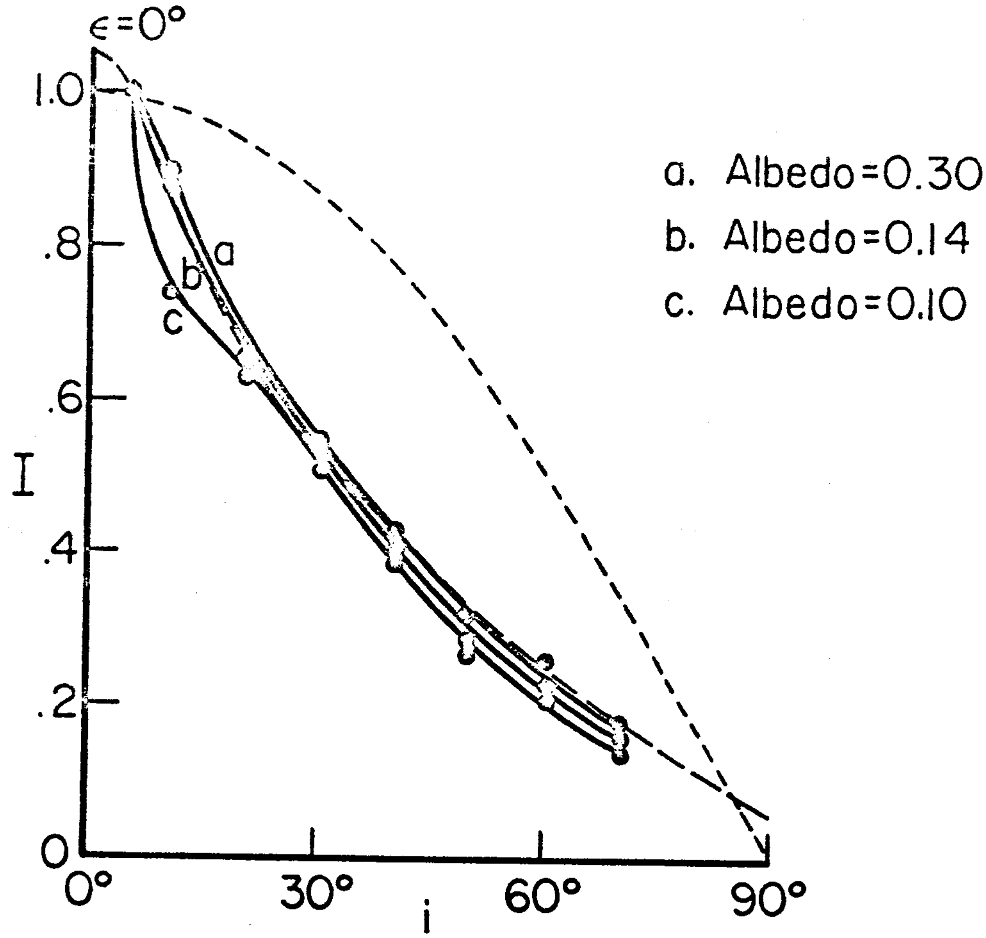
Figure 7



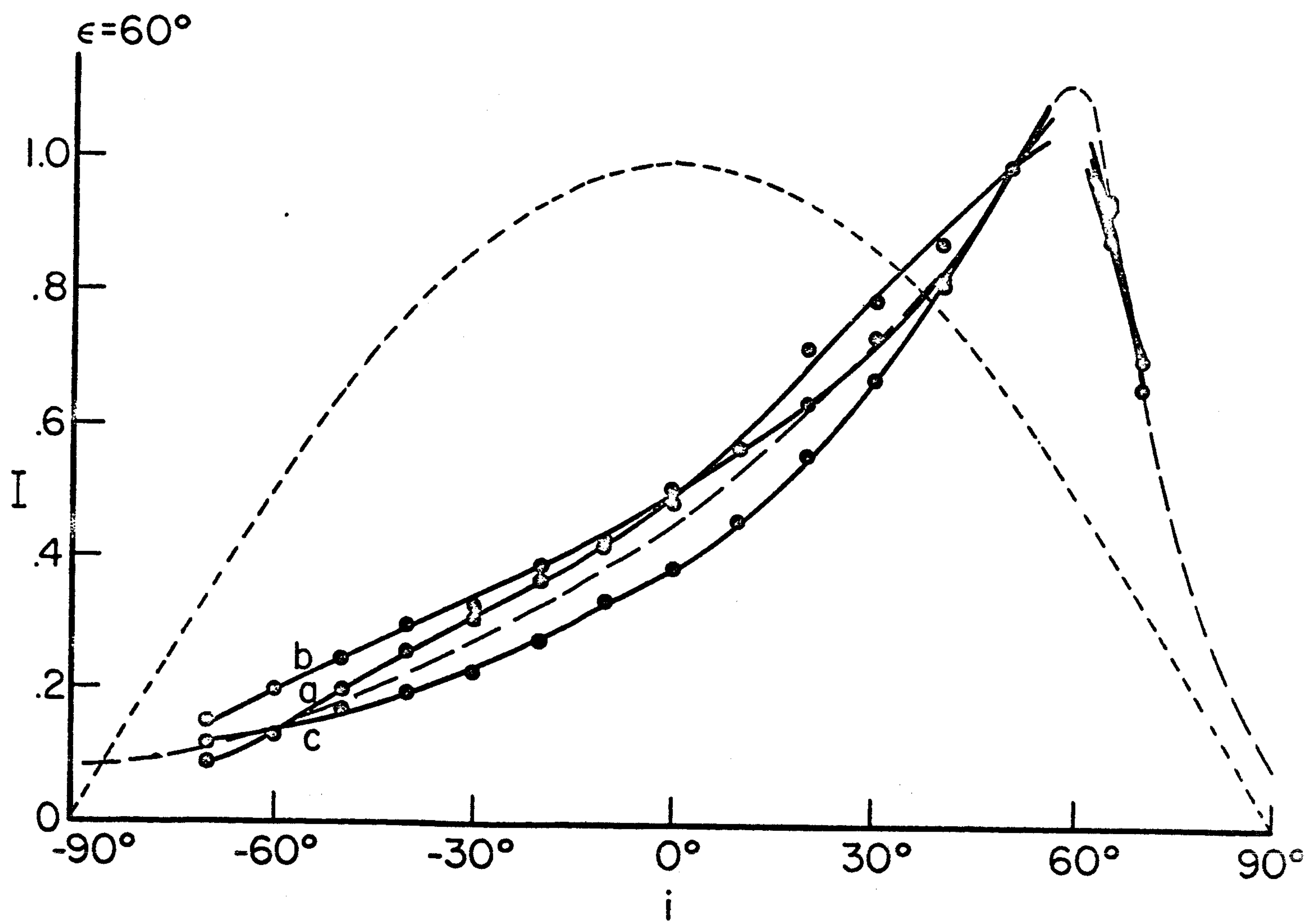
0
30°
%o
30
20
10
0
-10
-20
C
D
A
B
A
E
%o
80
60
40
20
0
-20
20
0
-20
0
30
60
90
120
150
180°

Figure 8

Fig. 9a



ε=0°
a. Albedo=0.30
b. Albedo=0.14
c. Albedo=0.10
I
i
1.0
.8
.6
.4
.2
0
0°
30°
60°
90°
a
b
c



ε=60°
I
i
1.0
.8
.6
.4
.2
0
-90°
-60°
-30°
0°
30°
60°
90°
a
b
c

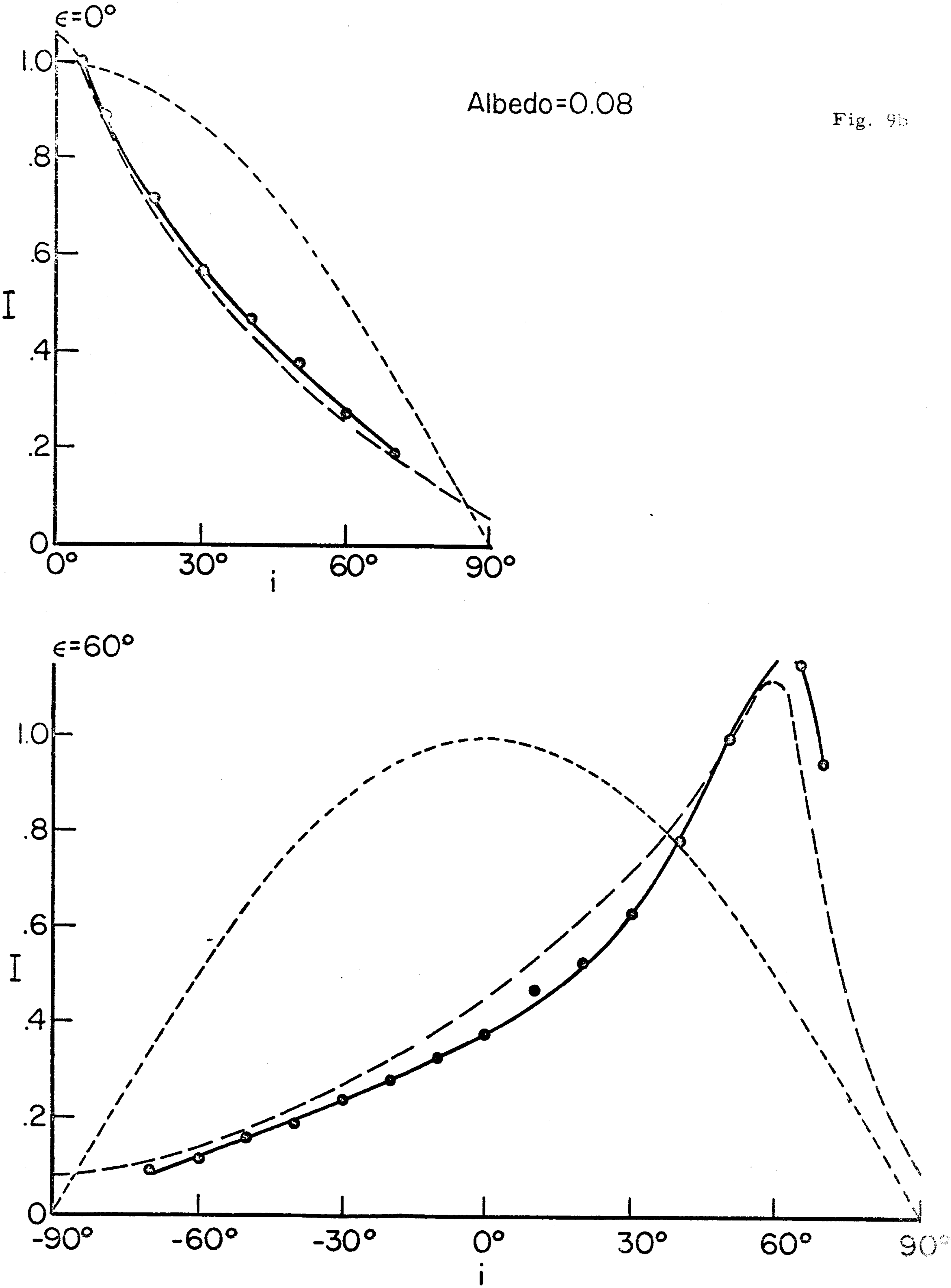

ε=0°
Albedo=0.08
1.0
.8
.6
I
.4
.2
0
0°
30°
60°
90°
i
ε=60°
1.0
.8
.6
I
.4
.2
0
-90°
-60°
-30°
0°
30°
60°
90°
i

Fig. 9b

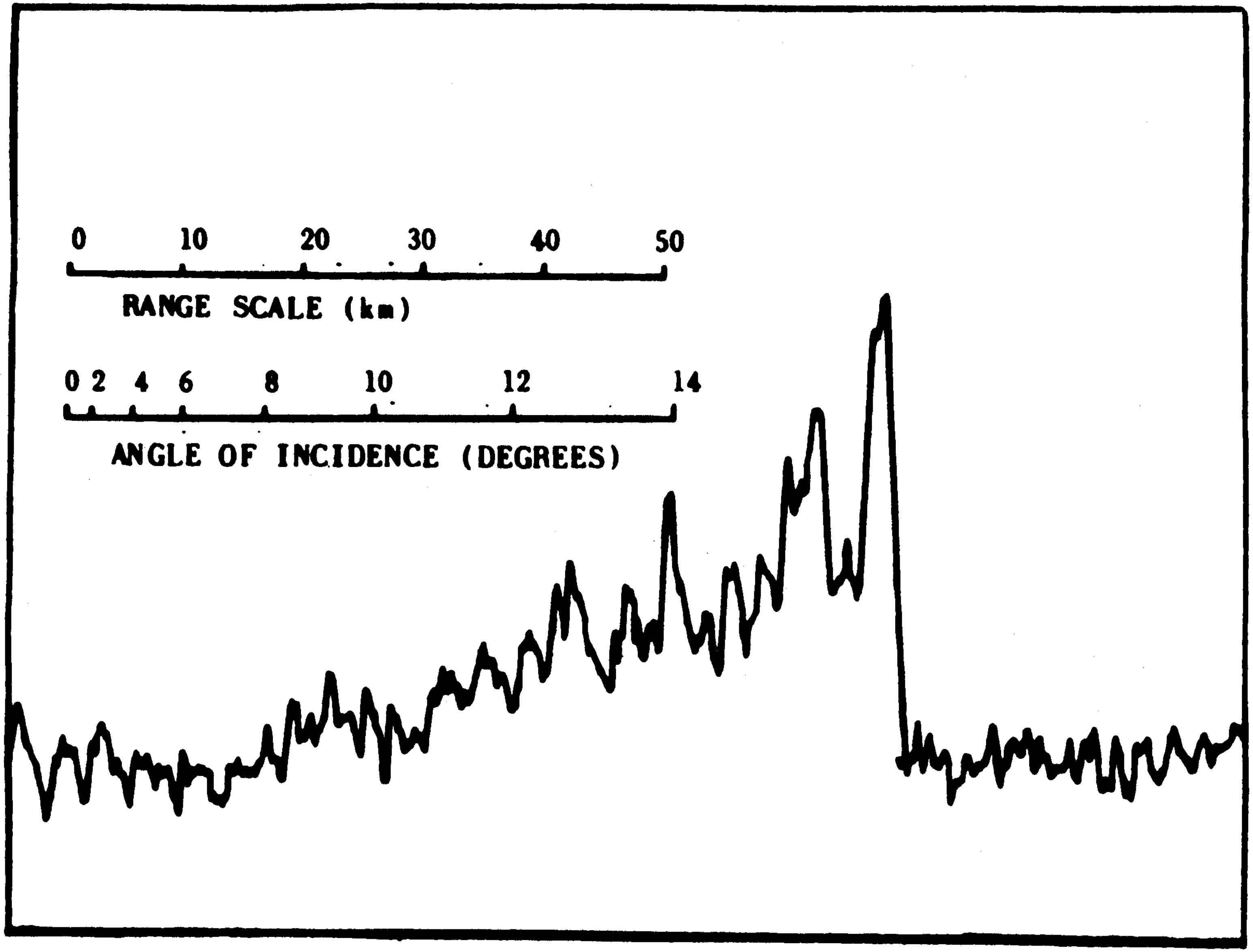
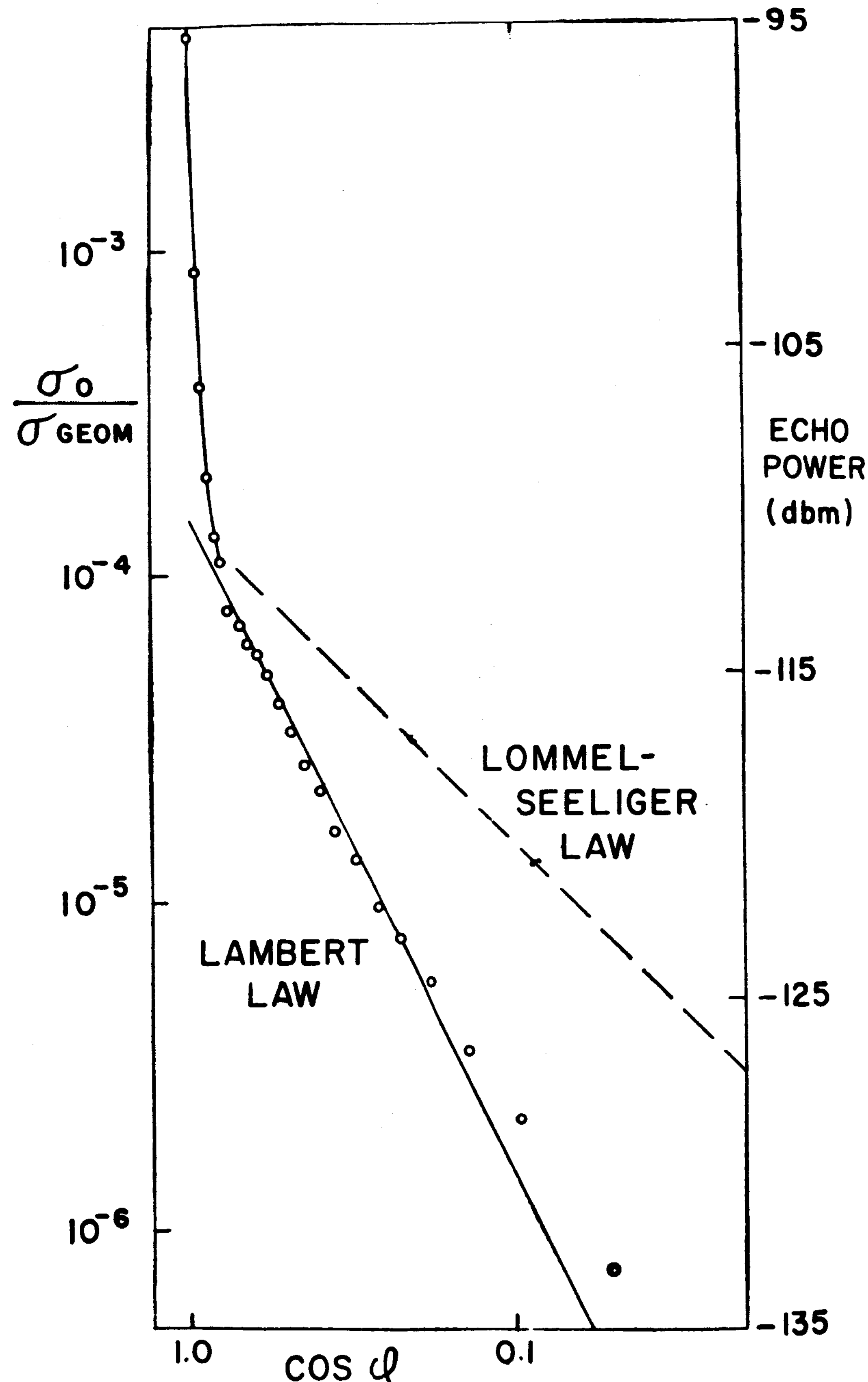

0 10 20 30 40 50
RANGE SCALE (km)
0 2 4 6 8 10 12 14
ANGLE OF INCIDENCE (DEGREES)

Figure 10



10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\frac{\sigma_0}{\sigma_{GEOM}}$
-95
-105
-115
-125
-135
ECHO POWER (dbm)
LOMMEL-SEELIGER LAW
LAMBERT LAW
1.0
0.1
COS ϕ

Figure 11

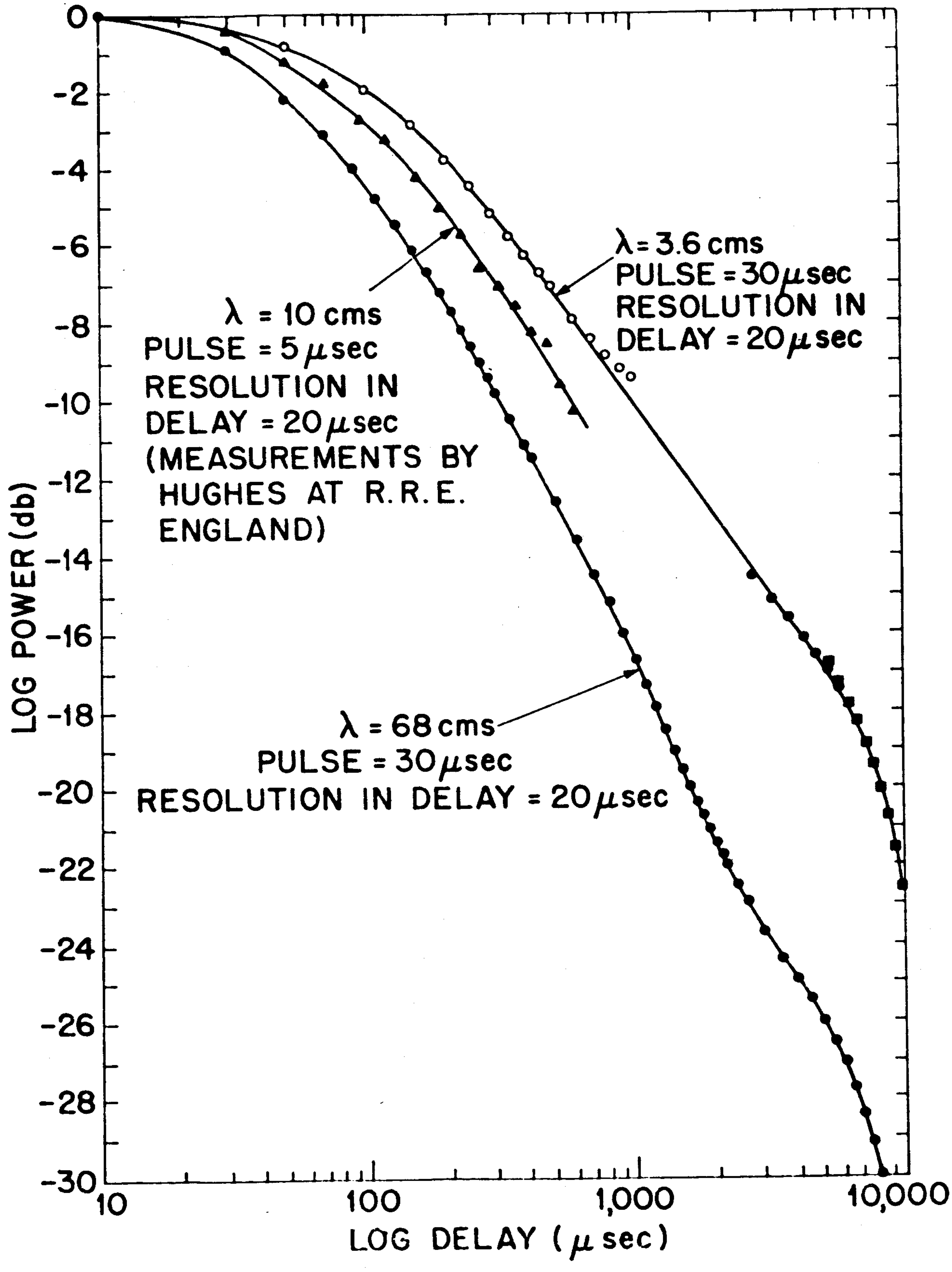
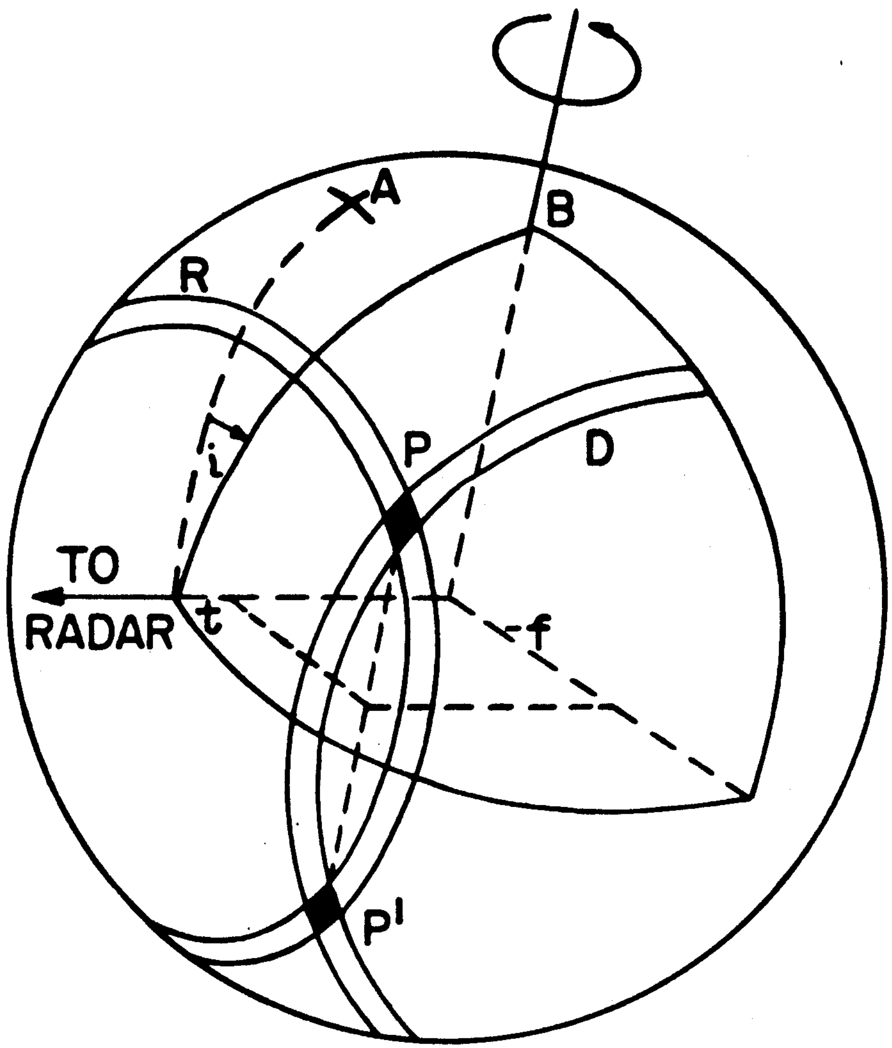

0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
LOG POWER (db)
10
100
1,000
10,000
LOG DELAY (μ sec)
λ = 3.6 cms
PULSE = 30 μsec
RESOLUTION IN
DELAY = 20 μsec
λ = 10 cms
PULSE = 5 μsec
RESOLUTION IN
DELAY = 20 μsec
(MEASUREMENTS BY
HUGHES AT R.R.E.
ENGLAND)
λ = 68 cms
PULSE = 30 μsec
RESOLUTION IN DELAY = 20 μsec

Figure 12



A: NORTH LUNAR POLE.

B: POLE OF APPARENT ROTATION.

D: DOPPLER CONTOUR FOR RELATIVE FREQUENCY, f.

P, P': CONJUGATE POINTS.

R: RANGE CONTOUR FOR RELATIVE RANGE, t.

Figure 13

Figure 2 shows one of the isothermal maps that recently have been made at Lowell (Geoffrion *et al.* 1960). The map was made by scanning the Moon in a television-like raster obtained from astronomical motions. Rotation of the Earth carried the telescope and receiver across the Moon in about 2 minutes to make the horizontal scans. Every 3 minutes the telescope was moved ahead to produce another scan. The vertical scanning was produced by the Moon's motion in declination. When the Moon is near the celestial equator, only about 3 hours are required to observe the whole Moon. The resolution employed has been about 25 seconds of arc and is commensurate with the distance between scans. About 60 scans in all are obtained.

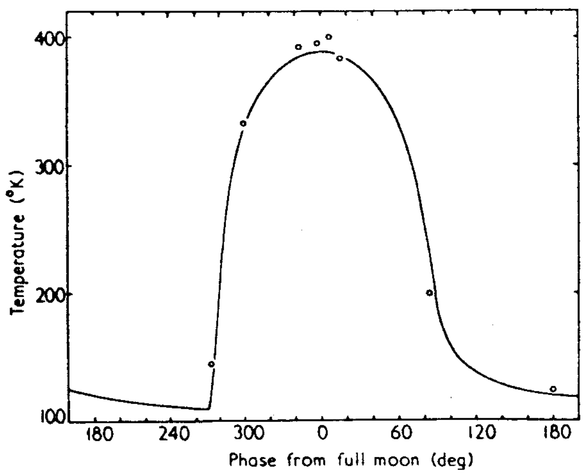
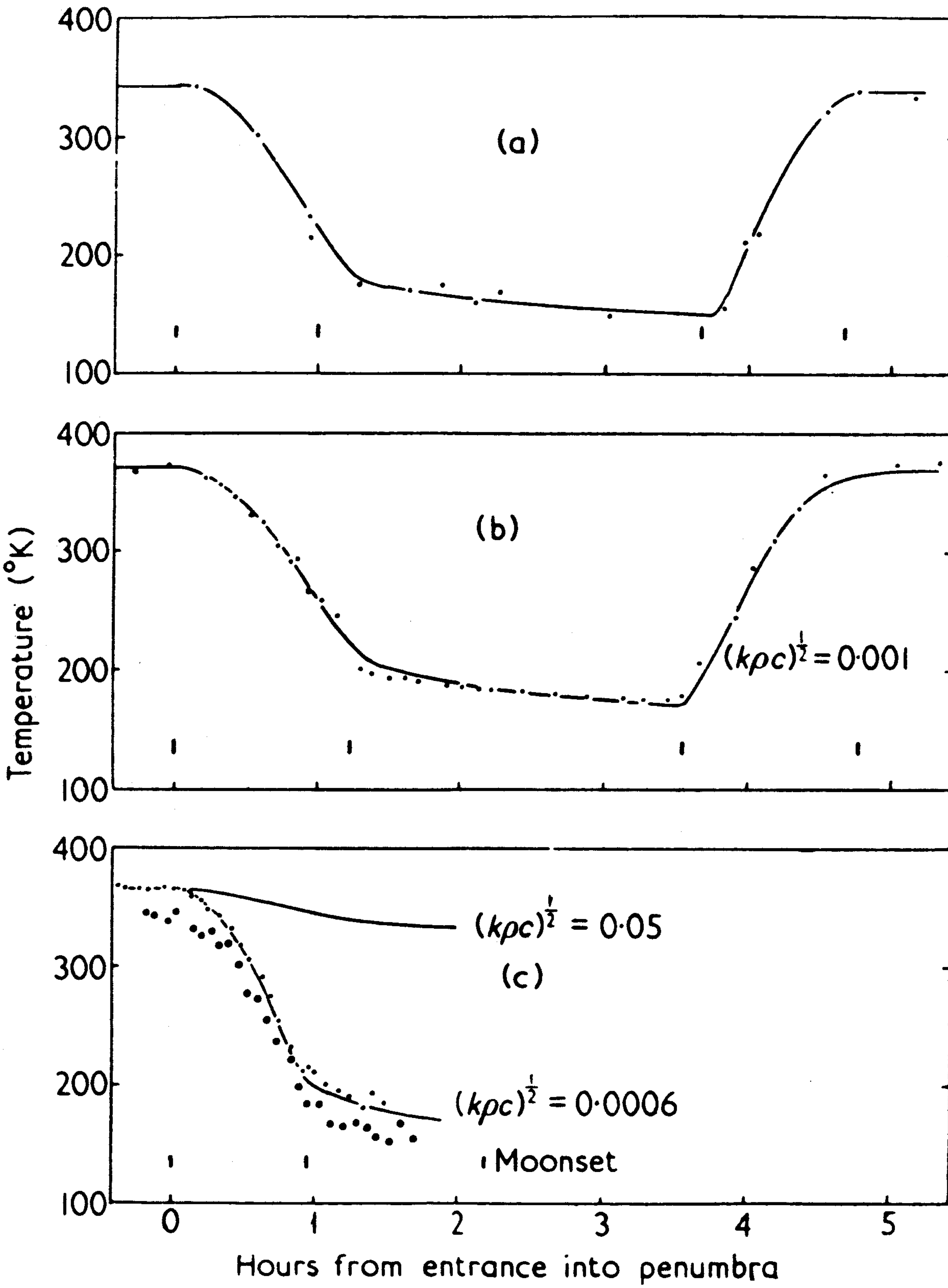


Fig. 14 Some temperature measurements of the lunar surface throughout a lunation. The curve is a theoretical one with $(k\rho c)^{\frac{1}{2}} = 0{\cdot}0023$.

We may concentrate our attention on the measurements made at or near normal incidence of a point near the centre of the disk and establish the variation of the temperature throughout a lunation. From the maps of isotherms recently made at Lowell, we have taken some points on the illuminated part of the Moon and combined these with the measurement of the "midnight" temperature mentioned above, with the result shown on Fig. 3. Observations are being continued to complete this curve.

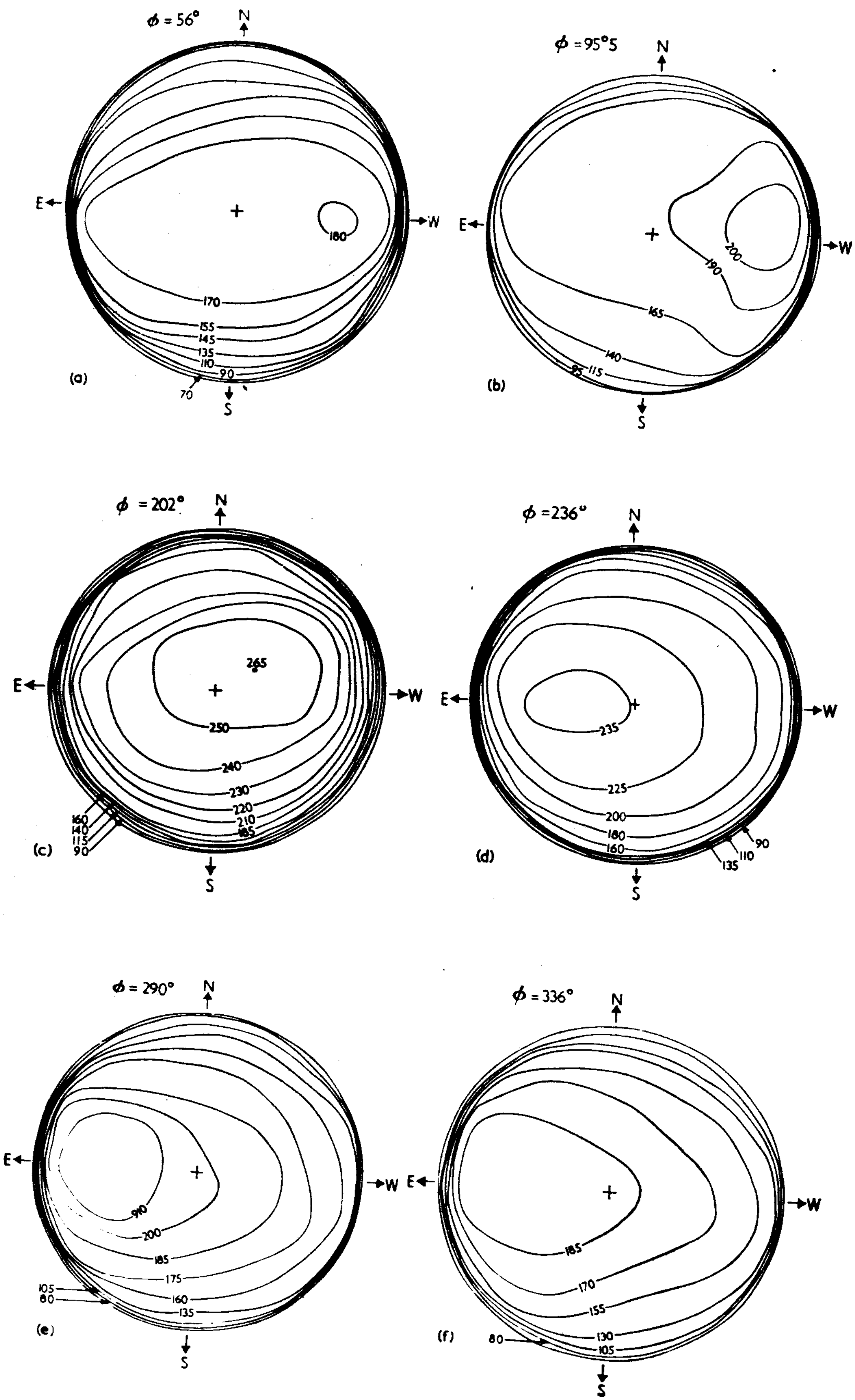
III. Temperature of Moon in Eclipse

Perhaps the most important single piece of information comes from measurements of the course of lunar temperatures during a total eclipse. Pettit and Nicholson (1930) measured a point only 48 seconds



400
300
200
100
(a)
(b)
$(k\rho c)^{\frac{1}{2}} = 0{\cdot}001$
Temperature (°K)
(c)
$(k\rho c)^{\frac{1}{2}} = 0{\cdot}05$
$(k\rho c)^{\frac{1}{2}} = 0{\cdot}0006$
Moonset
0
1
2
3
4
5
Hours from entrance into penumbra

Figure 15



φ = 56°
N
E
W
S
180
170
155
145
135
110
90
70
(a)
φ = 95°5
200
190
165
140
115
95
(b)
φ = 202°
265
250
240
230
220
210
185
160
140
115
90
(c)
φ = 236°
235
225
200
180
160
135
110
90
(d)
φ = 290°
210
200
185
175
160
135
105
80
(e)
φ = 336°
185
170
155
130
105
80
(f)

Figure 16

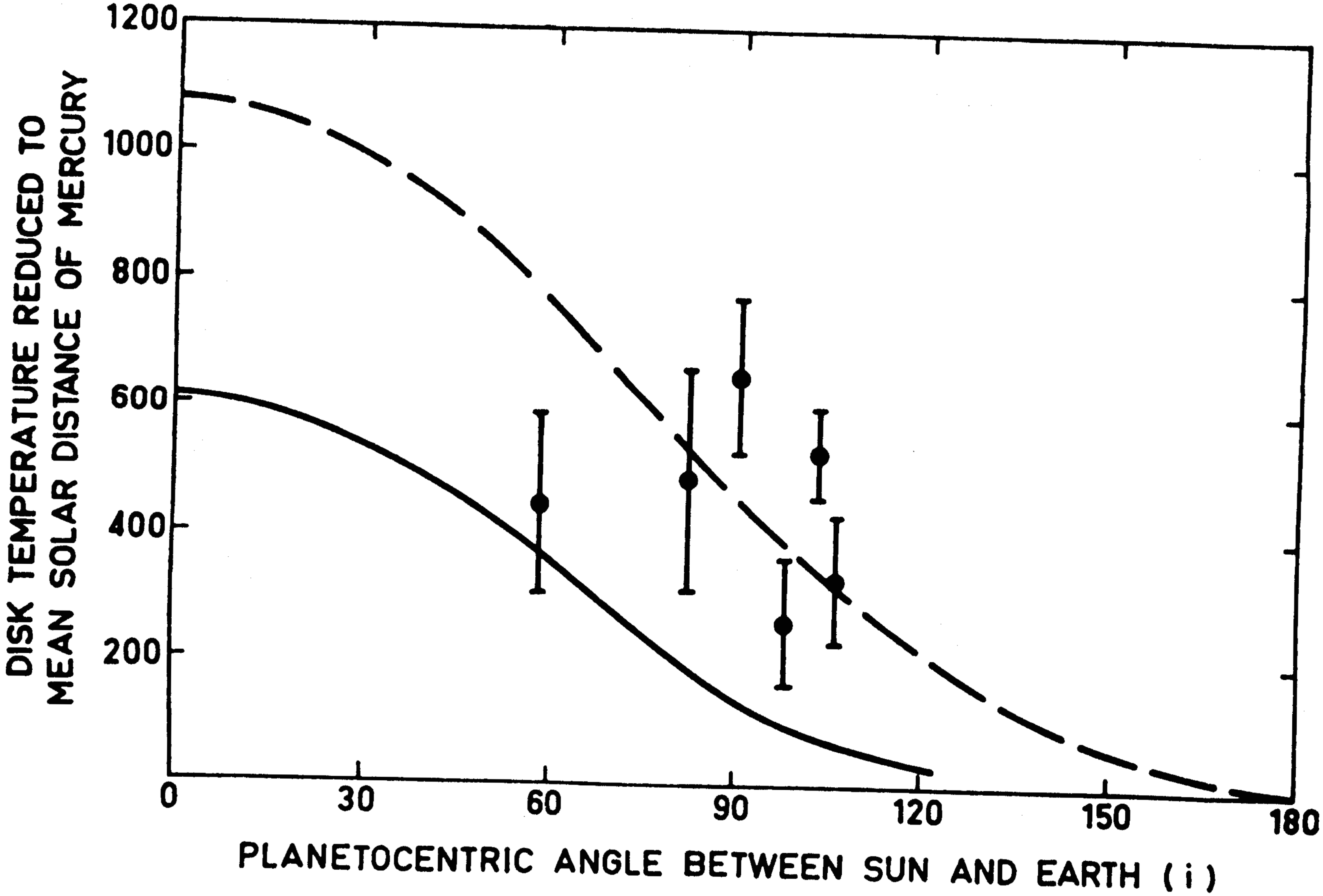

DISK TEMPERATURE REDUCED TO
MEAN SOLAR DISTANCE OF MERCURY
1200
1000
800
600
400
200
0
30
60
90
120
150
180
PLANETOCENTRIC ANGLE BETWEEN SUN AND EARTH (i)

Figure 17

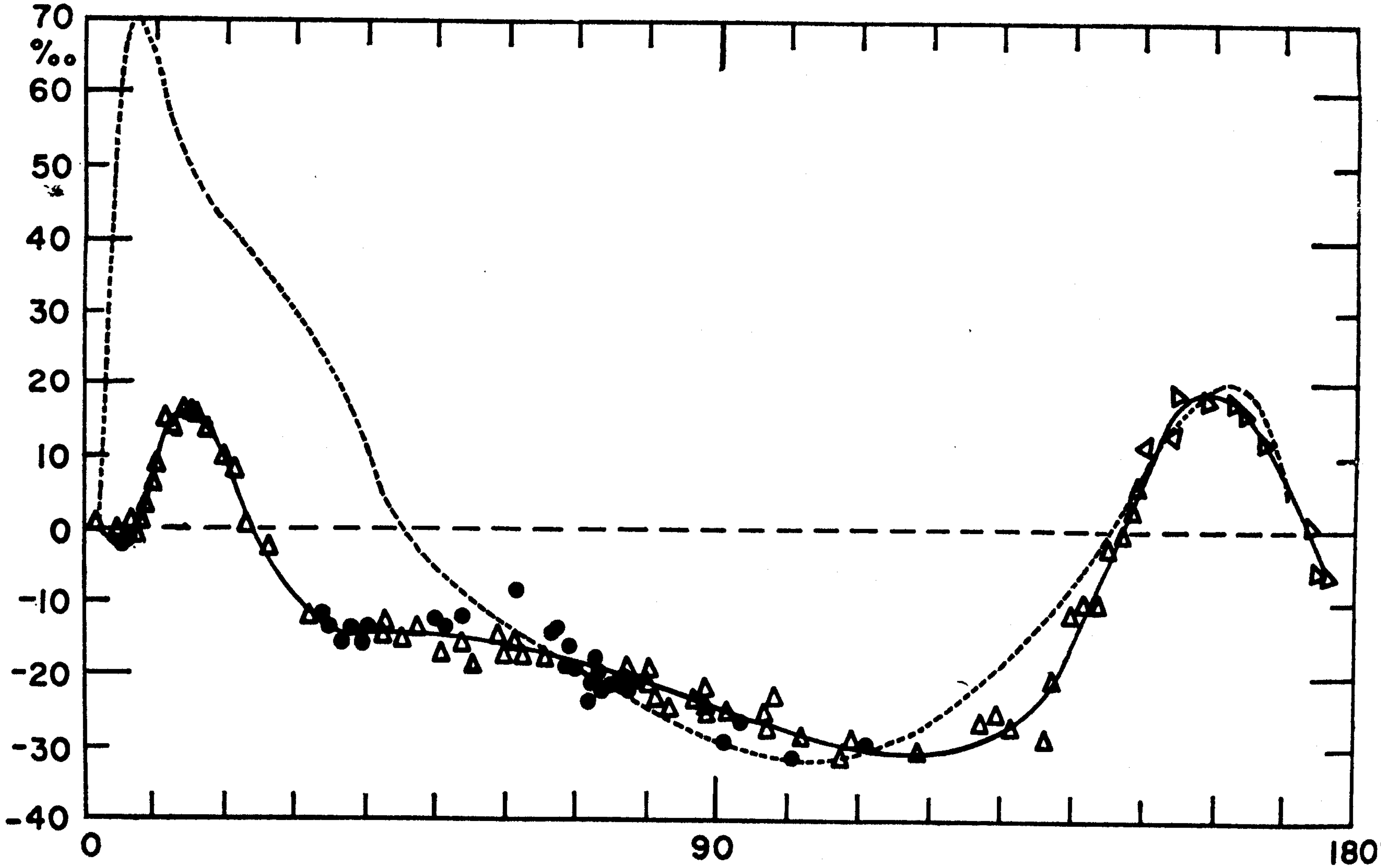


Figure 18

VENUS SPECTRUM, KPNO-36, JUNE 15, 1962 (I) 1.9 - 2.5μ

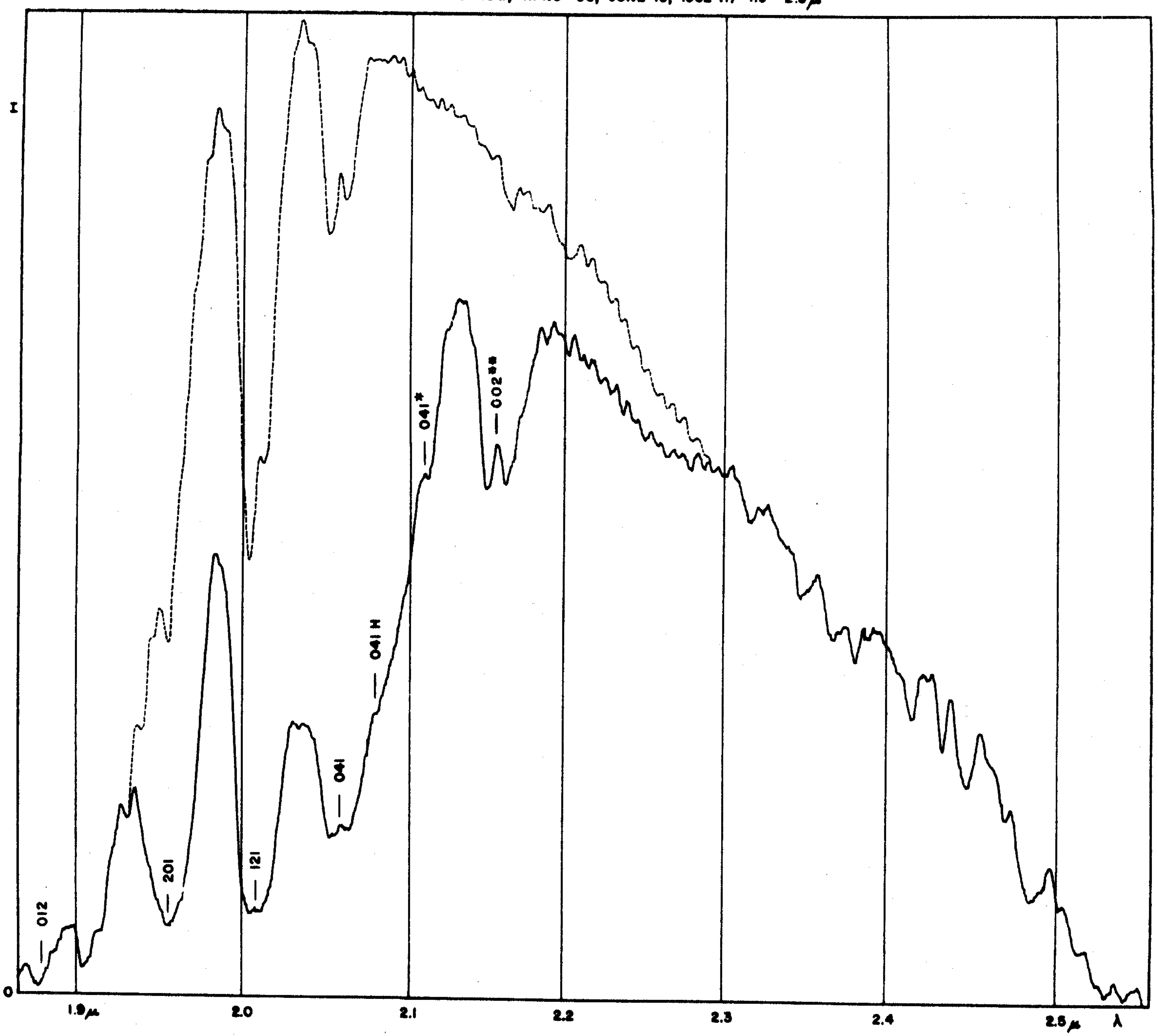


Figure 19a

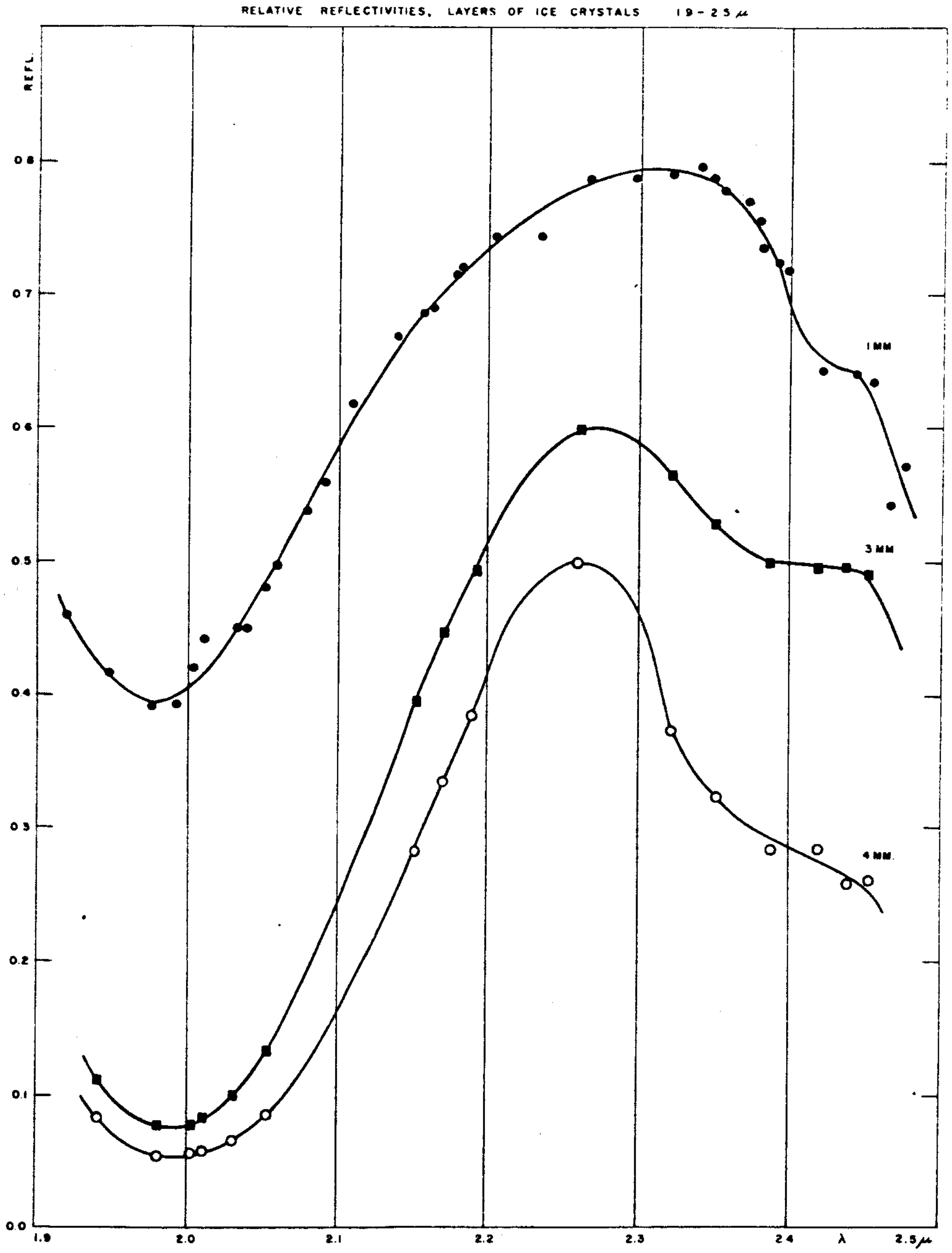


Fig. 19b Reflectivities of layers of ice crystals 1 mm, 3 mm, and 4 mm thick, derived from Figure 7*a*. The *shapes* of the curves are fixed by the ratios measured from Figure 7*a*; the scales of the ordinates cannot be found from the measures and have been chosen somewhat arbitrarily.

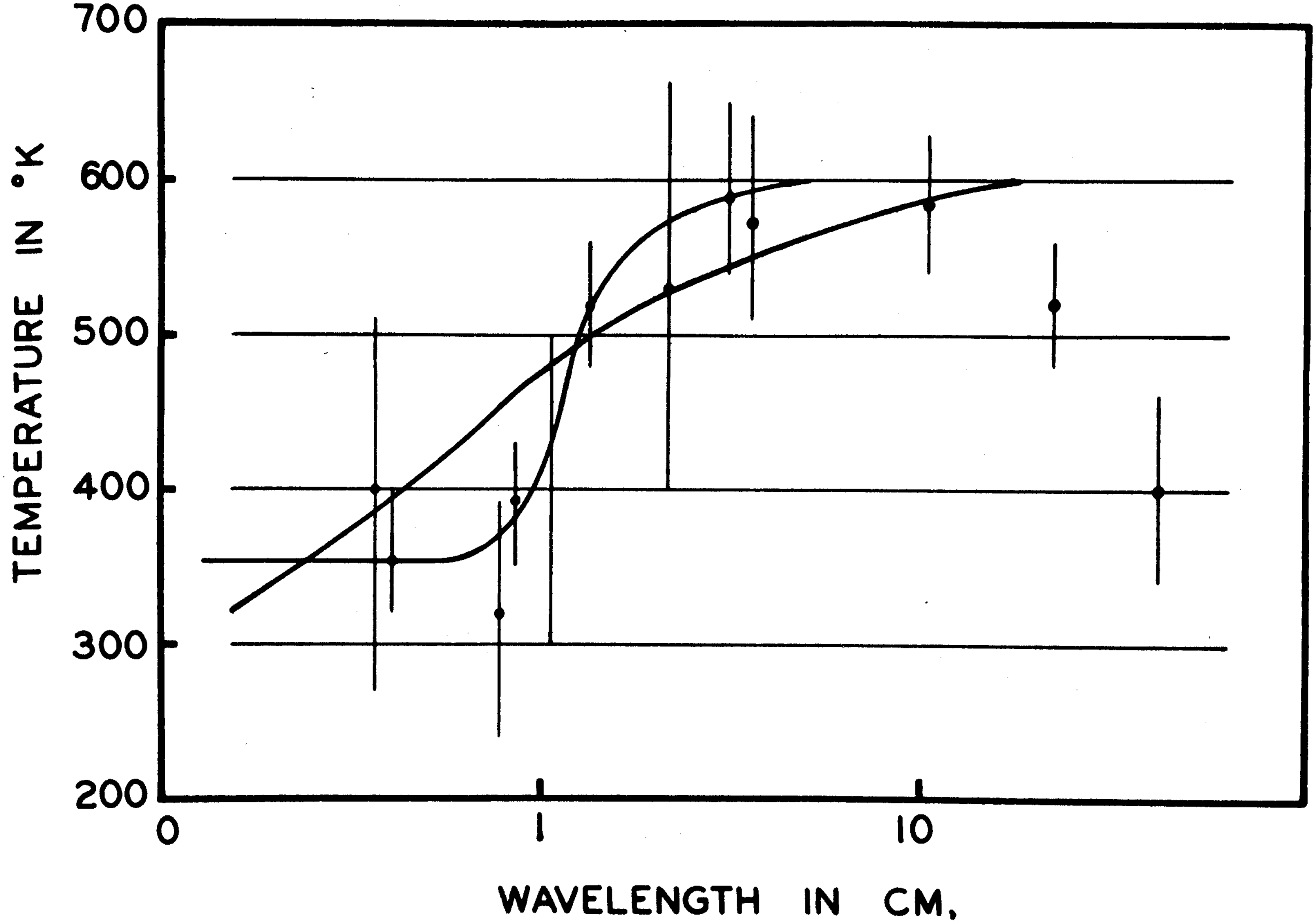
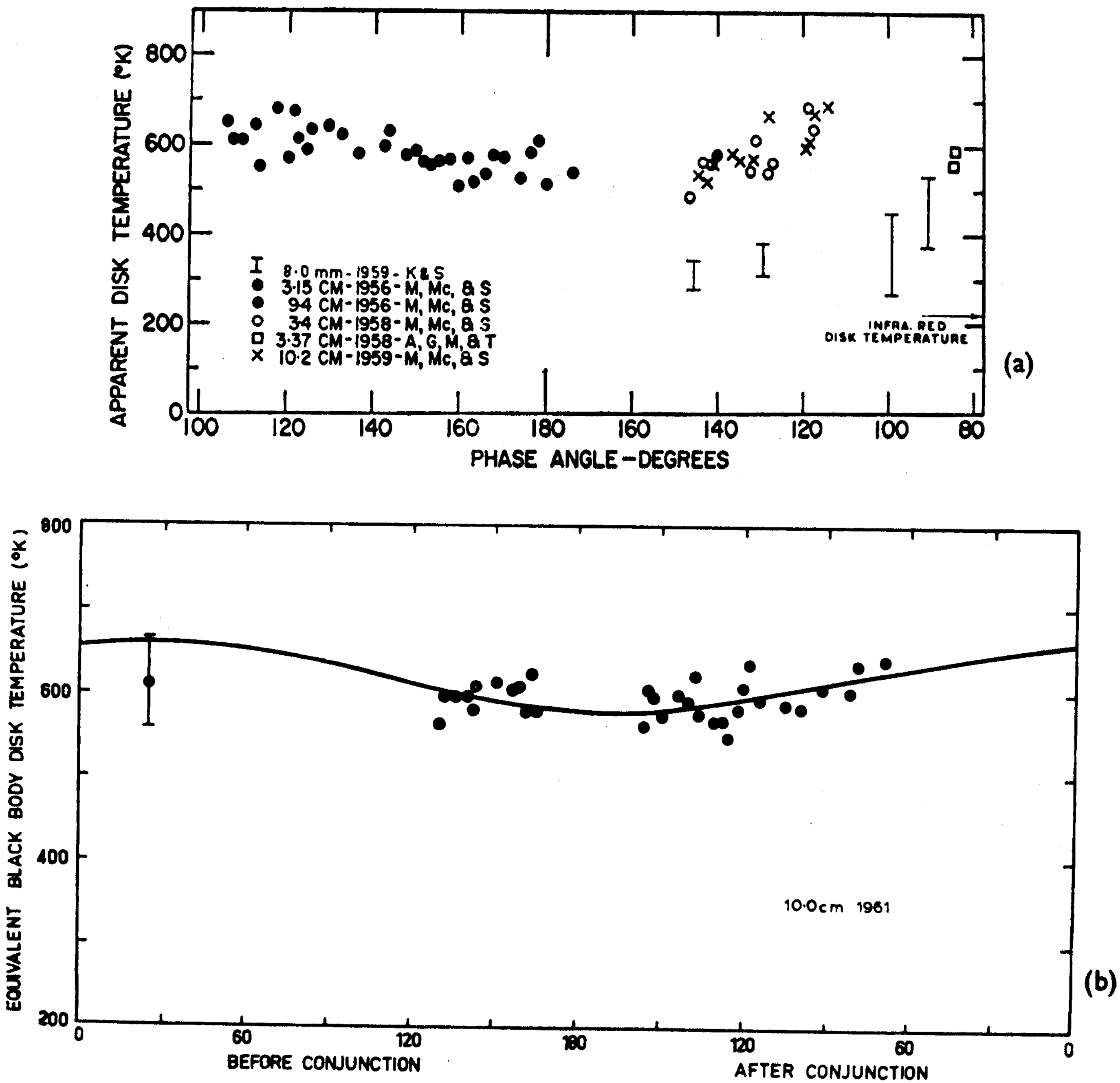

700
600
500
400
300
200
TEMPERATURE IN °K
0
1
10
WAVELENGTH IN CM.

Figure 20



APPARENT DISK TEMPERATURE (°K)
PHASE ANGLE — DEGREES
8·0 mm - 1959 - K & S
3·15 CM - 1956 - M, Mc, & S
9·4 CM - 1956 - M, Mc, & S
3·4 CM - 1958 - M, Mc, & S
3·37 CM - 1958 - A, G, M, & T
10·2 CM - 1959 - M, Mc, & S
INFRA RED
DISK TEMPERATURE
(a)
EQUIVALENT BLACK BODY DISK TEMPERATURE (°K)
10·0cm 1961
BEFORE CONJUNCTION
AFTER CONJUNCTION
PHASE ANGLE (i)
(b)

Figure 21

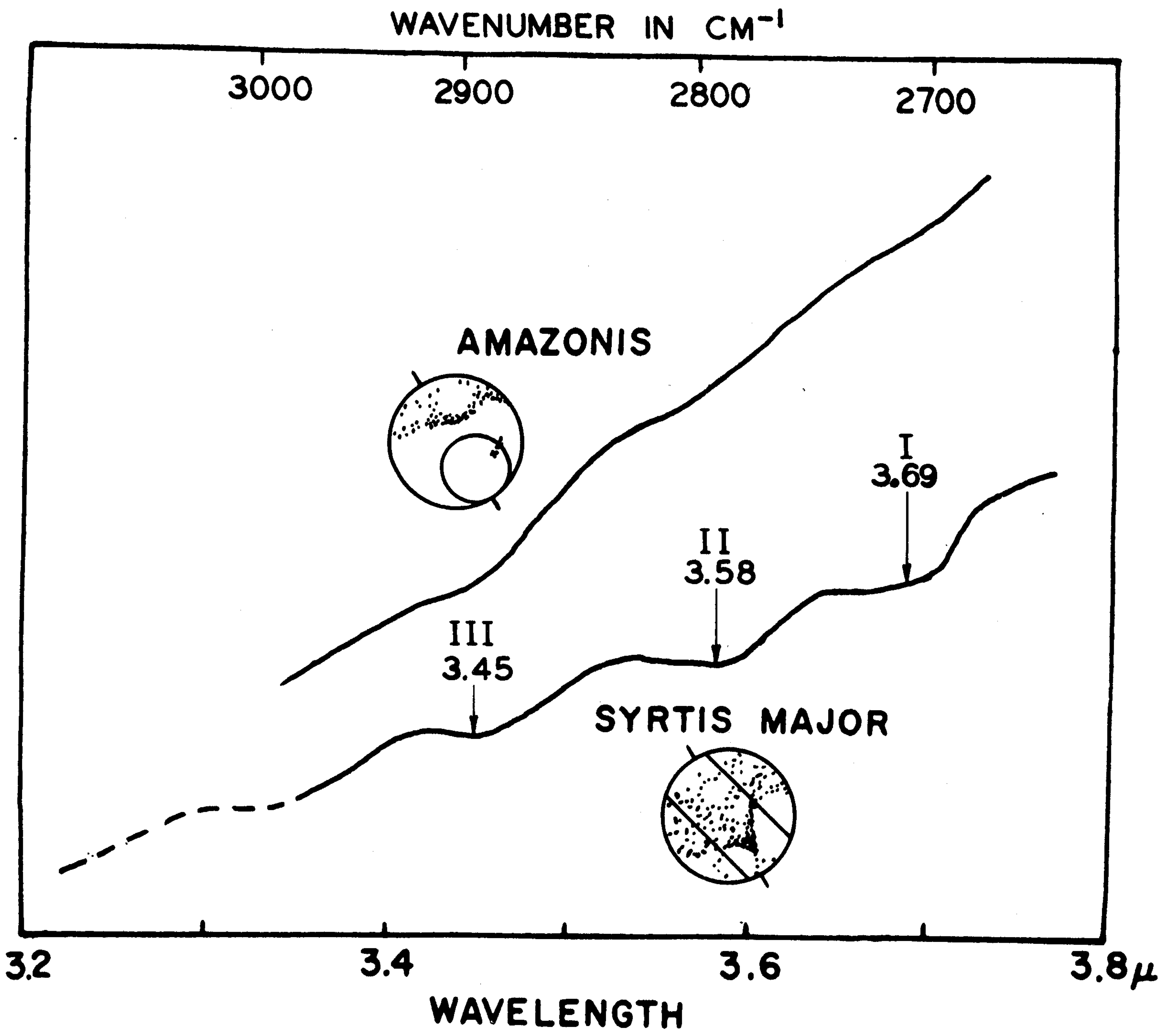

WAVENUMBER IN CM⁻¹
3000
2900
2800
2700
AMAZONIS
I
3.69
II
3.58
III
3.45
SYRTIS MAJOR
3.2
3.4
3.6
3.8μ
WAVELENGTH

Figure 22

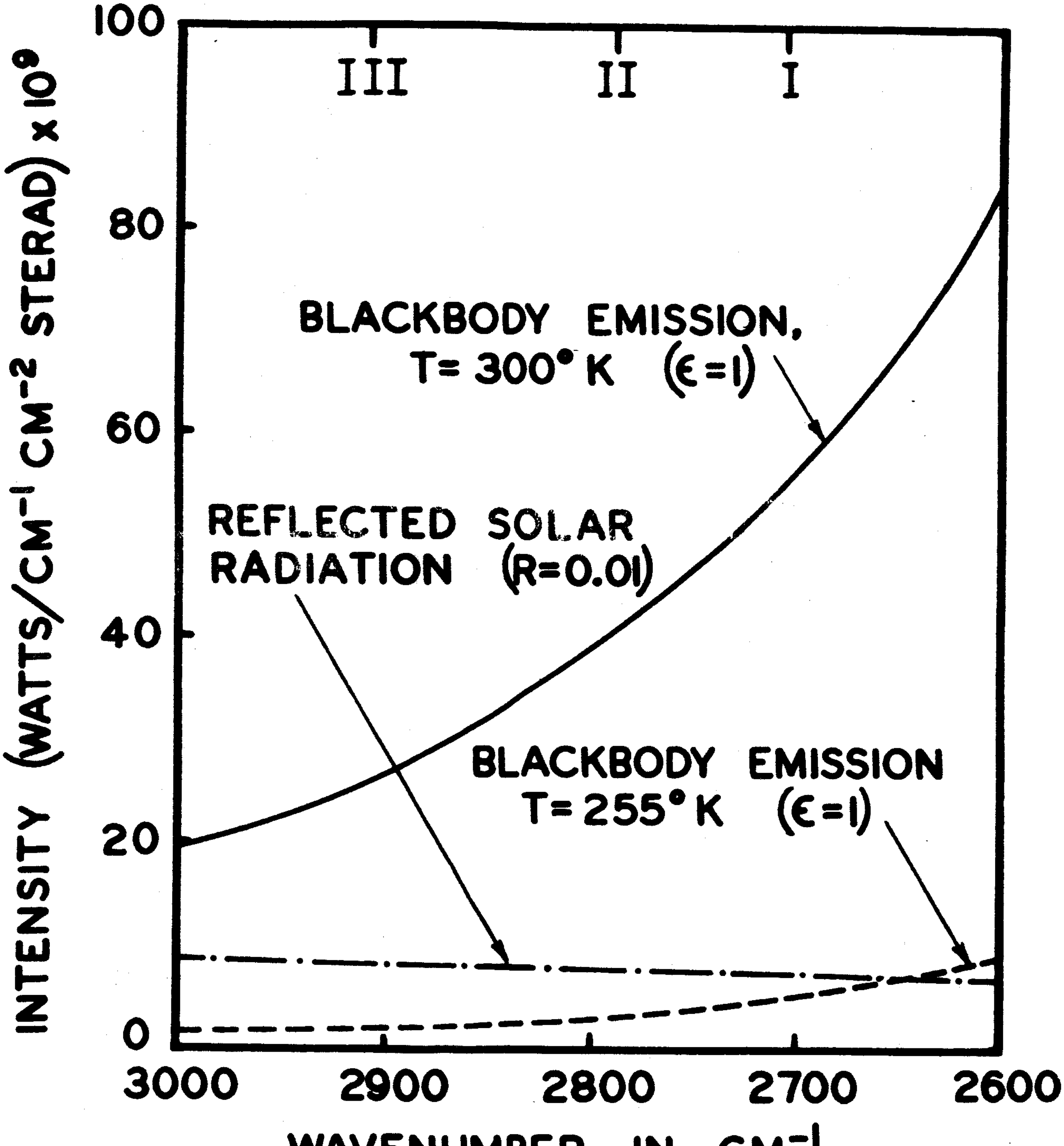

100
80
60
40
20
0
INTENSITY (WATTS/CM^{-1} CM^{-2} STERAD) x 10^{9}
III
II
I
BLACKBODY EMISSION, T= 300° K (ε=1)
REFLECTED SOLAR RADIATION (R=0.01)
BLACKBODY EMISSION T=255° K (ε=1)
3000
2900
2800
2700
2600
WAVENUMBER IN CM^{-1}

Figure 23

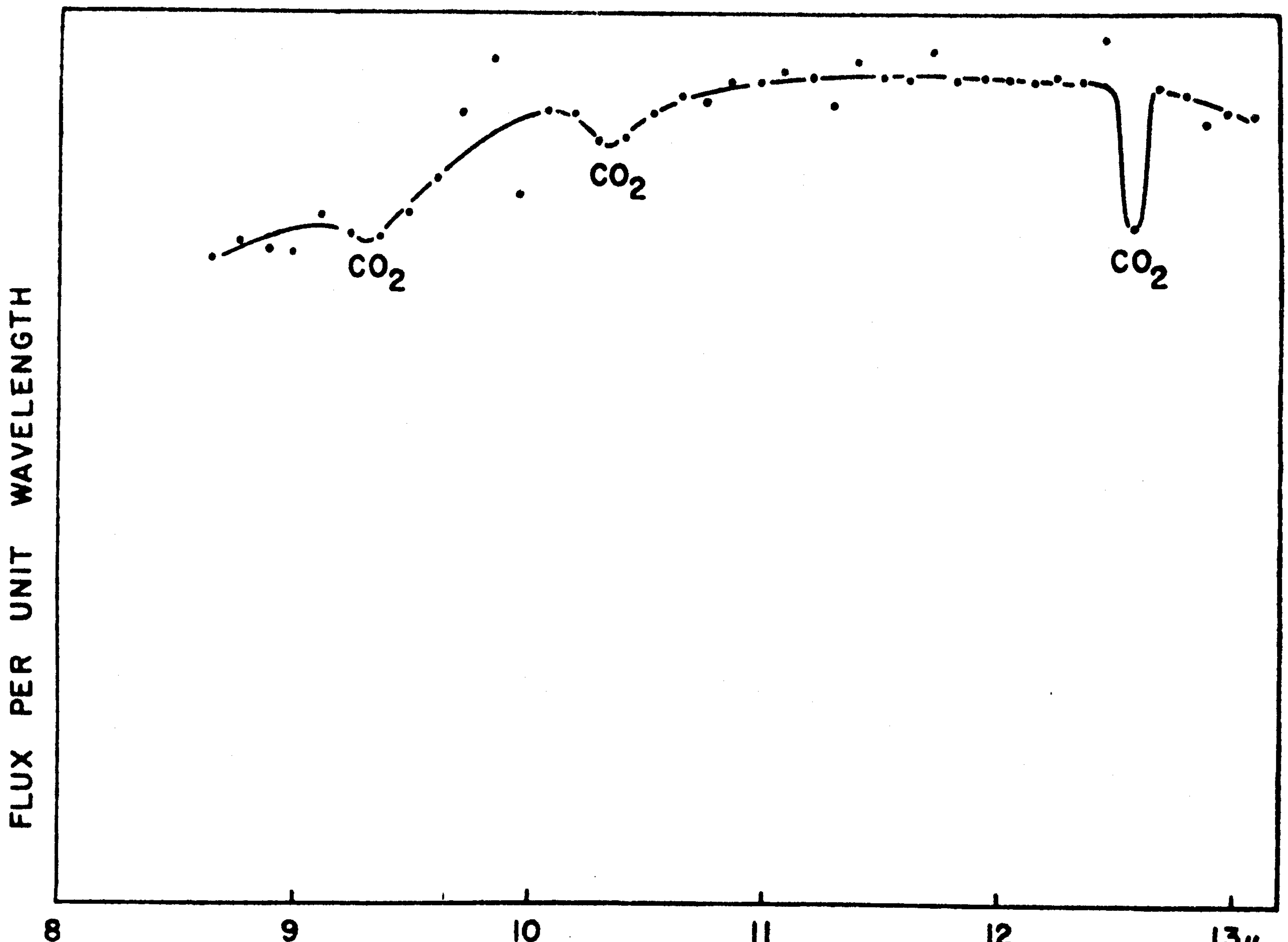


Figure 24

TABLE 1

Albedos of the Planets

	R/R_E	p(U)	p(B)	p(V)	p(R)	p(I)	qv	$A_{(v)}$
Mercury	0.38	....	0.076	0.100	0.145	0.179	0.563	0.056
Venus	0.961	0.353	.492	.586	....	....	1.296	.76
Earth	1.000	....	....	.367	....	....	1.095	.36
Mars	0.523	.052	.080	.154	.286	.310	1.04	.16
Jupiter	(11.20, 10.46)	.270	.370	.445	.466	.347	1.65	.73
Saturn	(9.48, 8.48)	.211	.316	.461	....	....	1.65	.76
Uranus	3.72	.530	.603	.565	.325	.119	1.65	.93
Neptune	3.38	.585	.624	.509	.248	.091	1.65	.84
Pluto	0.45	0.099	0.111	0.130	0.154	0.152	1.04	0.14

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